METHUEN'S TEXT-BOOKS OF TECHNOLOGY

ELECTRIC LIGHT AND POWER

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PREFACE

THIS book represents a preliminary course for students of Electrical Engineering, and is based upon some fifteen years of teaching experience.

The student engaged in electrical industries approaches the subject from a point of view which is entirely different from that of the ordinary student of physics; unlike the latter, he is in daily contact with electrical appliances, and experience and observation have given him a certain amount of knowledge of their action. But he is deficient in breadth of view, and requires careful initial training to develop correct habits of thought. For his purposes the most useful course is one in which exact discussion is subordinated to the exposition of fundamental principles, and in which commercial applications are regarded mainly as object lessons.

If he wishes to proceed further he must of necessity acquire some knowledge of mathematics, chemistry, and general physics. A good deal of progress in these subjects can be made during the first year of study, and it is therefore very desirable that too much purely electrical work shall not be attempted in this year. It is better to lay a foundation on which a mathematical and more detailed treatment can be based later on.

Our thanks are due to the various firms whose names are mentioned in the text for the loan of blocks, diagrams, and for other assistance in the preparation of this book.

E. E. B.
W. H. N. J.

PREFACE TO THE NINTH EDITION

IN preparing the revised ninth edition of ' Electric Light and Power,'' the modern tendency towards an increasing use of alternating currents has been catered for by the addition of chapters dealing in a simple manner with the properties of alternating currents and with the more important appliances met with on alternating current circuits. It is hoped that these additions will not only make the book more useful to students of elementary electrical engineering but will also make it particularly serviceable to students preparing for the examinations in Electrical Installation Work under the recently revised scheme of the City and Guilds of London Institute. Such students, in addition to their specialised work, are required to have a very considerable knowledge of elementary electrical principles, and their requirements in this respect are covered by the material in the new edition.

In addition, the whole of the descriptive matter has been brought up to date and the nomenclature brought into line with modern conventions.

W. H. N. J.

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CHAPTER I

LINES OF MAGNETIC FLUX

CONSIDER a steel bar magnet. Experiment shows us at once that either end possesses the power of attracting iron, and that this property gradually becomes weaker towards the middle, where it practically disappears.

If, instead of using unmagnetised iron, we try its effect on another magnet, conveniently by using a light pivoted " compass needle," we find a new property; repulsion is now obtained as well as attraction, and it is noticeable that these actions take place when the magnet is some distance from the iron or compass needle.

The importance of this last fact is apt to be overlooked, for here we transcend the bounds of ordinary experience; in daily life we never see a thing move without a reasonably obvious cause (falling bodies excepted), and yet here it apparently occurs.

Even at this early stage it is as well to emphasise the statement that the ordinary mechanical laws do hold good in this case also: the compass needle only moves because something pushes it; it is not that there is no link or connection between it and the deflecting magnet, only that we are dealing with a refined form of machinery invisible to our eyes.

This property of repulsion in addition to attraction indicates that the two ends of our magnet are not identical in all respects, and this becomes still further evident if we suspend it freely, for then it points in a direction nearly North and South. Hence we define the " North pole " of the magnet as being that pole which tends to point towards the North, the South pole being defined in a corresponding manner, and from our

observations we at once deduce the rule that between two North poles, or two South poles, there is repulsion, and between a North and a South pole attraction.

Our magnet is probably too massive to be easily broken, but if we can do so, we shall learn that each half becomes a perfect magnet with North (N) and South (S) poles.

This experiment is more easily carried out with knitting needles, magnetised by stroking them with one pole of a magnet, and its repetition will convince us that we cannot in this way obtain a magnet with a single pole.

Further evidence cannot well be given here, and so we shall simply state that this result is confirmed by experience, and that it is also impossible to obtain a magnet with poles of unequal strength, although one may be spread over a larger area than the other.

The power possessed by a magnet of conferring its own properties on unmagnetised steel, alluded to above, now demands attention.

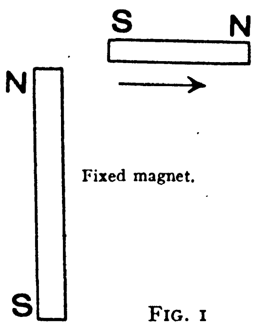


FIG. 1

Here we find a rod of hard iron or steel to be permanently magnetised in a definite way when drawn over the pole of a magnet in one definite direction; the end of the rod which leaves the pole last is always of opposite polarity to the pole used. If the experiment is repeated, using soft iron, the latter becomes very weakly magnetised, the less so the softer and purer it is. We can easily show that this is not because the soft iron is incapable of becoming magnetised, for if we hold it in contact with the magnet pole as shown in Figure 2, and then dip the end into iron filings, a large number adhere to it, which, however, practically all drop off again when the magnet is slipped away.

A hard steel bar held similarly may pick up very few filings, but these will adhere after the magnet is removed.

Further, the experiment may be tried in the form shown in Figure 3, where the soft iron bar is supported in front of the magnet poles; it then readily attracts filings whilst the magnet is near, and a small compass needle will show that the

bar is magnetised as indicated in the figure, but this magnetisation is largely lost when the inducing pole is removed; yet not wholly lost, as delicate tests will show the bar to be still

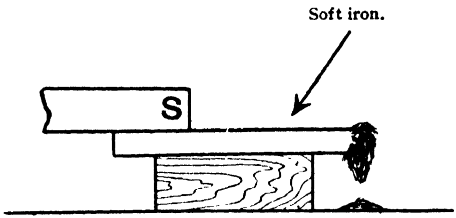


FIG. 2

very feebly magnetised, and this residual effect will force itself upon our attention later.

We have now briefly examined some of the evidence on which our first important generalisation is based: without attempting to do more than indicate its nature, it may be said that all research points to the conclusion that magnetism is a property of the atom and not of the mass.

We can conveniently group together and co-ordinate our

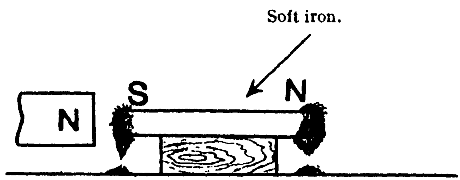


FIG. 3.

facts if we assume that each atom of iron is itself a complete and perfect magnet, without at present inquiring further into what such a statement involves.

From this point of view a mass of iron is always magnetised, and whether it shows any external magnetism or not is merely a question of the arrangement of the atoms: for an immense number of tiny magnets mixed together in confusion will produce little or no apparent external effect, whereas if some or all of them are arranged in due order, their effects will be added together and will become distinctly noticeable.

If we bring a magnet pole near a group of little pivoted compass needles, we see them arrange themselves in due order under its influence, and when we take it away we see them swing back into more or less irregular groups.

If we bring the magnet pole near a block of iron we may imagine the little atomic magnets striving to behave in the same way; if they succeed, or rather if some of them succeed in so turning, the iron appears to us to be magnetised, but obviously that very freedom of movement which allowed them to turn will also allow them to swing back again when the magnet pole is removed.

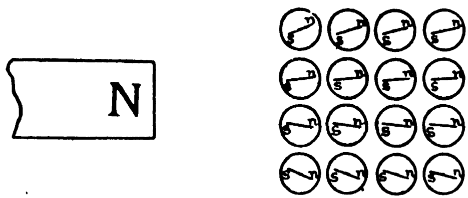


FIG. 4.

This idea of the particles in a mass of iron possessing possibilities of free rotatory motion may seem extravagant to some students; we can only remark here that the idea is abundantly justified by evidence obtained in other branches of physical science.

If we take the compass needles off their pivots and lay them on a flat surface, and then repeat the experiment, we see that they are now more difficult to move when the magnet pole is brought near, but that they retain their impressed configuration when the magnet pole is removed.

In some such way we must picture for ourselves the behaviour of steel or harder iron; we need not go too far and imagine that in steel we are necessarily concerned with ordinary mechanical friction, such ideas have been shown to be not really necessary.

Nor need we perplex ourselves at present with the names, such as "Retentivity" and "Coercive Force," which serve to express the facts; it is sufficient if we accustom ourselves to look below the surface of things, and in dealing experimentally with iron and magnets to try to imagine and realise the molecular actions involved.

Summing up, we may say that pure soft iron readily becomes magnetised when under the influence of some "magnetising force," and equally readily loses most of it when that influence is removed, whereas steel under the same conditions becomes less strongly magnetised, but retains its new state or a large portion of it indefinitely.

So far we have considered the action of a magnet from the point of view of attractions and repulsions between N and S

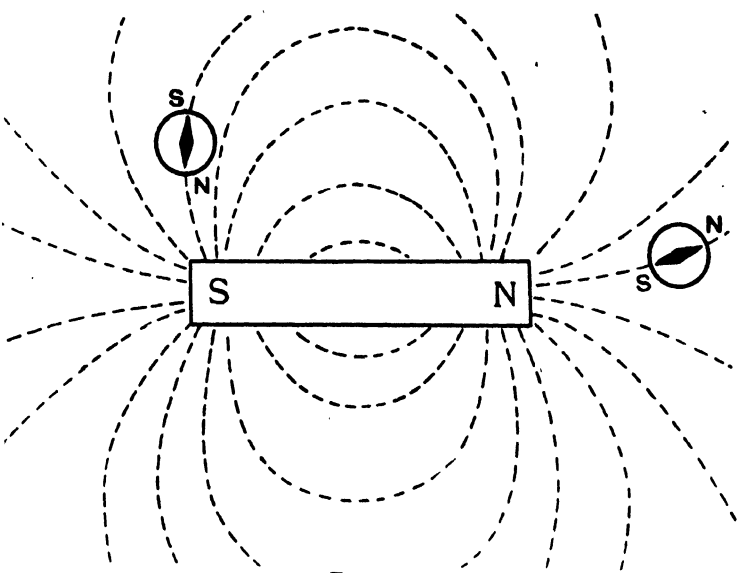


Fig. 5.

poles. Experience has shown, however, that such ideas are far less useful in practice than another way of picturing the phenomena, due originally to Faraday, in which we concentrate our attention on the properties of the space outside the magnet, rather than upon the properties of the tangible magnet itself.

The basis of the method is to be found by examining Figures 5, 6, and 7, which show the arrangements produced

in iron filings or compass needles placed in the space around a magnet or magnets.

The filings arrange themselves in perfectly definite and regular chains which form curved lines extending from pole to pole, and the direction of a line at any point is the direction in which a compass needle tends to set itself at that point.

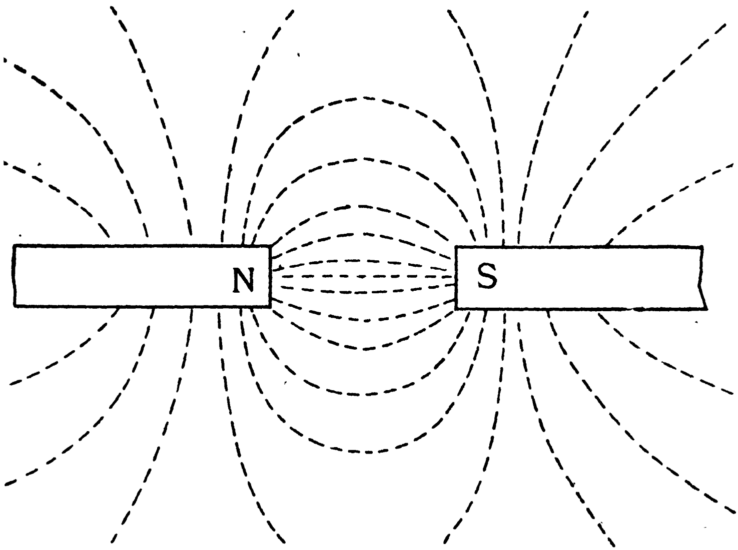


FIG. 6.

There is no particular mystery about these figures; they can be deduced easily from the consideration of the attractions and repulsions of magnet poles, and really, as stated above, only show the equilibrium position of a small magnet near a larger one.

Now, by an effort of the imagination, we may take a bold step in advance; it being evident that the space around a magnet does possess special properties, which must be due to the existence of some invisible structure or machinery whose nature is quite unknown, we may endeavour to define the properties of this space in any simple way which is in

accordance with the experimental facts. We shall henceforth consider a magnet as possessing a definite number of lines of magnetic flux[1], all of which pass through it and return outside, and which it carries about it wherever it goes, the direction of these lines outside the magnet being made visible by our experiments with the filings. To avoid quite unnecessary

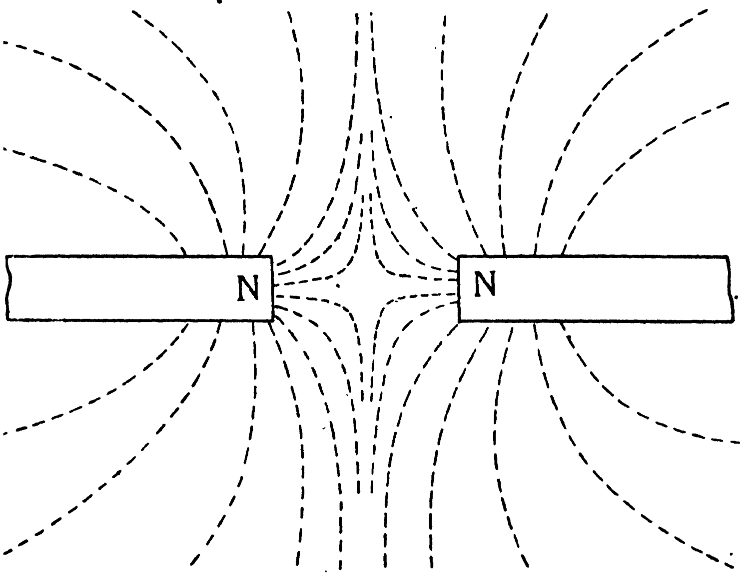


FIG. 7.

difficulties however it must be carefully kept in view, that although we shall for convenience speak of these lines as

[1] The idea underlying the use of lines of magnetic flux has been, and is, expressed in various ways. Such terms as "lines of magnetic force," "tubes of magnetic force," and others, each with its special meaning, have been employed. Since the purpose of this book is to give such simple explanations of electrical engineering problems as will appeal to students whose interests are essentially of a practical nature, it is thought that the term used in the text is the simplest and most useful in view of the varied phenomena and uses to which the lines are applied. The full name will often be abbreviated to "line of flux," "magnetic line," or even "line" when the context leaves no doubt as to the idea to be conveyed.

actual entities, yet they have no real existence, and only possess the merit of correctly indicating, in a way easy to follow, the action and properties of something which really does exist. At present we shall only use these lines of magnetic flux from the qualitative point of view, but quantitative properties will be assigned to them later. They have direction and are conventionally regarded as emerging from a N pole and entering a S pole.

The most important properties which we must ascribe to these lines of magnetic flux are as follows :—

1. *Lines of magnetic flux always tend to contract in length, and to ~~repel each other sideways~~.*

The evidence for this statement is, that whenever we find by using filings or a compass needle that lines of flux connect two iron or steel surfaces, we also find that there is an attraction between these surfaces, and we may consider it to be due to the contractile tendency of the lines.

Further, whenever lines of flux run side by side in the same direction they tend to repel each other laterally, and in the case of Figure 7, showing the arrangements of the lines between two like poles, it corresponds to an actual repulsion.

2. *Lines of magnetic flux always form closed curves.*

This is verified by moving a compass needle along a line of flux, when it is found that the line always returns again to the magnet. An apparent exception occurs if we take a direction which extends too far into space, and then we must believe it does return although we are unable to follow it : for if this were not so, the influence of the magnet would end abruptly at some point, whereas it extends indefinitely into space, simply getting weaker as distance increases. We have no actual knowledge of the region inside the magnet itself, but it is consistent with information obtained in other ways to regard the line of flux as completing its curve therein.

3. *Lines of magnetic flux never cut one another.*

For as the direction of a line is the direction in which a little magnet sets itself, to say that two lines intersect at some point amounts to the statement that in that place a little magnet would tend to point two ways at once.

When two sets of lines of flux of independent origin exist in the same space they really merge into one resultant set of lines which have a perfectly definite direction.

For suppose a pivoted magnet is at rest in its usual N and S direction (a condition which we can now ascribe to its tendency to point along the lines of flux belonging to the earth), then if we bring a magnet near, as shown in Figure 8, so that it produces another set of lines roughly at right angles

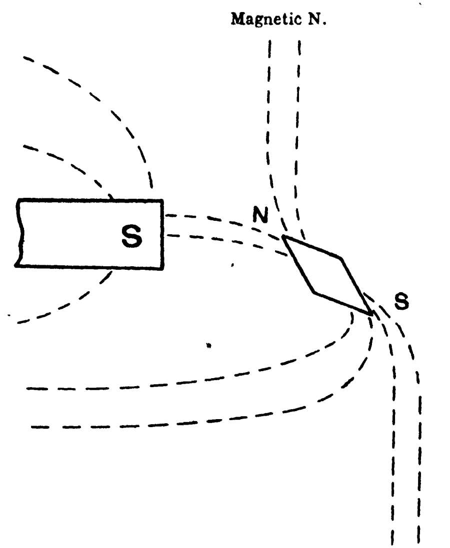


FIG. 8.

to those of the earth, the two will together produce a single set of lines of flux inclined to the direction of both of its components, and the pivoted magnet turns until it points along this new direction.

4. *Lines of magnetic flux are not diverted by any substances except iron or the few other magnetic substances.*

That is, we may say that they pass through all media with equal readiness except iron (or the few other magnetic

substances), but that they prefer to pass through iron whenever possible and will bend out of their way to do so.

We can illustrate this by the following experiment :— A bar magnet is placed near a compass needle, provided with a scale and pointer, until some convenient deflection is produced ; then we may introduce between them any kind of obstacle without altering the deflection provided it does not contain iron (or a magnetic substance) ; this means we have not disturbed the lines of flux (see Figure 9).

If a fair-sized piece of iron be interposed, however, the deflection is diminished, returning to its old value when the iron is removed, thus suggesting that the iron acts as an

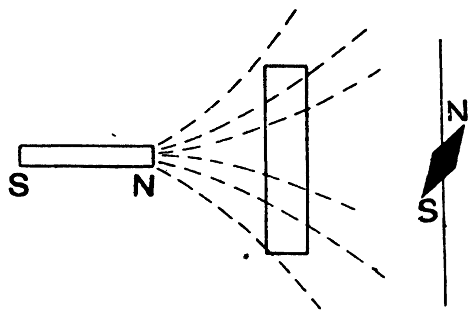


FIG. 9.

obstacle to the lines of flux : it certainly cuts off some of them, but this is because it favours their return towards the other pole of the deflecting magnet (see Figure 10).

5. *A space in which lines of magnetic flux exist is called a "magnetic field."*

For instance, the field of a bar magnet is in the region around and it extends indefinitely into space. A magnet points very nearly N and S when it is free to move, because it is in the magnetic field produced by the earth.

6. *When a piece of iron is put into a magnetic field, it tends to become magnetised.*

For each atomic magnet will endeavour to point the right way along the lines of flux ; an instance of this is shown in Figure 4.

7. *If a magnet (or a piece of iron which becomes magnetised as above) is placed in a magnetic field it tends to set itself as far as possible parallel to the lines of magnetic flux, and further, it tends to move into the strongest part of the field.*

This property may also be expressed by saying that a piece of iron, or a magnet, placed in a magnetic field always tends to set itself so that as many lines of flux as possible can pass through it.

This is illustrated by the behaviour of iron filings to a

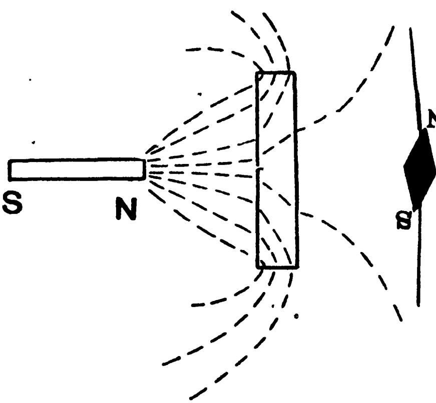


FIG. 10

magnet; they not only form chains, but also move up to the poles if possible, where the lines of flux are crowded closest together.

8. *The poles of a magnet are simply those parts from which lines of magnetic flux emerge.*

This statement of the properties of lines of magnetic flux is incomplete and will be extended later; but it is all we really need for the present, and to over-elaborate the subject would only confuse a beginner.

It may however be remarked that a stronger field will naturally be symbolised by packing a greater number of lines into a given space. Hence the crowding together of the lines at the poles of the magnets shown in the previous figures indicates that the field is there strongest.

CHAPTER II

THE MAGNETIC EFFECT OF AN ELECTRIC CURRENT

WE have now to show that lines of magnetic flux, identical in all respects with those possessed by a magnet, can be produced by an electric current without using any iron at all.

We shall assume that suitable current from a battery or electric lighting mains is available, and that we may regard it as flowing in a certain direction, leaving the elementary principles of current circuits to be dealt with in a later chapter.

If we connect the terminals of a fairly powerful battery B by a copper wire E D (if accumulators are used a certain amount of resistance placed in series will be necessary) and dip it into iron filings, we find that the filings cling to it all along its length and drop off again when the circuit is broken[1] (see Figure 11).

The result cannot be due to the wire itself becoming magnetised, because copper is not a magnetic substance, and further, the same effect is obtained whatever the wire be made of, though if the current is too weak the action may not be very noticeable.

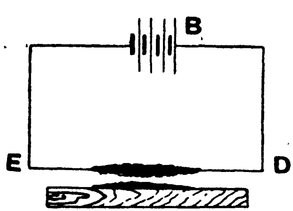


FIG. 11.

Next send a strong current through a vertical conductor passing through a sheet of cardboard on which iron filings are scattered. On tapping the card the filings arrange themselves roughly in circles around the wire. This experiment shows that lines of magnetic flux exist in circles

[1] A rather strong current is required for these two experiments if good results are to be obtained.

round the wire whilst it is carrying a current, and we can confirm this conclusion by placing a few compass needles on the cardboard; when current passes they will arrange themselves as shown in Figure 12.

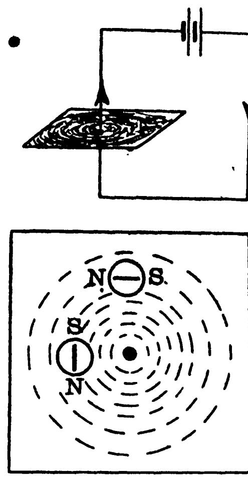


FIG. 12.

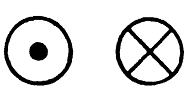
We thus learn that a current in a straight conductor produces a magnetic field in the space around it, the lines of flux in the simplest case being concentric circles around the conductor; this fact is of fundamental importance.

The behaviour of the iron filings in the first experiment is now accounted for, it being merely a particular case of the property number 7 ascribed to lines of flux.

The filings set themselves along the lines of flux, and therefore transversely to the conductor; and their tendency to move into the strongest part of the field causes them to cling to the conductor as if the latter attracted them, whereas the property is in the space and not in the conductor itself.

Similarly we can see that a magnet free to move, such as a compass needle, will always tend to place itself at right angles to a conductor carrying a current. This was the first discovered fact connecting electricity and magnetism, and it is usefully applied in the simplest type of galvanometer.

If we try the experiment by holding the wire above, and parallel to, a compass needle, we shall find that the direction of the deflection produced changes when the direction of the current is changed by reversing the battery connections.



Current outwards. Current inwards.

FIG. 13.

Hence (as in the case of those produced by a permanent magnet) there is the idea of direction to be associated with lines of flux, and it is necessary to frame some simple rules for grouping the facts together. For this purpose simple diagrams are very helpful, and they will usually require the conductor to be shown in section.

In accordance with a useful notation, introduced by Professor Silvanus Thompson, we shall use an X to denote a current going away from us, and a dot to represent a current coming towards us (see Figure 13).

If we take a vertical conductor and place a compass needle

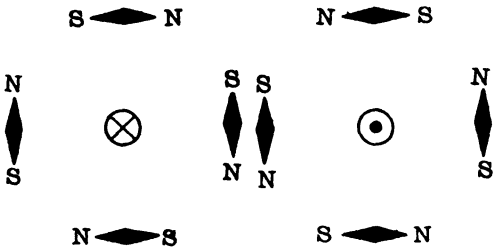


FIG. 14.

in various positions round it we shall find the results are as shown in Figure 14.

Many rules have been suggested to express these facts, but personally we prefer the oldest :—

Imagine yourself swimming head first in the direction of the current with arms outstretched and facing towards the magnet in question ; then its North pole will be on your left hand.

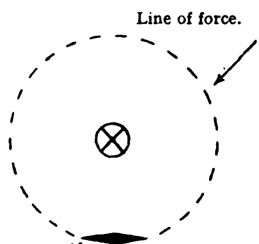


FIG. 15.

Now the magnets arrange themselves tangentially to the circular lines of flux ; if they were flexible they would bend into an arc of a circle.

Further, Figure 15 suggests the idea that the two poles tend to move around the conductor along the lines of flux in exactly opposite directions, and this idea is correct in principle and can readily be illustrated by experiment.

We cannot of course obtain a magnet with a single pole, but we can obtain practically the same result by making one pole inoperative.

One form of apparatus is shown in Figure 16.

Here a bent magnet N S is pivoted to permit of free rotation

about a vertical axis, and a conductor R M carries a current parallel to it for half its length. This conductor dips into a mercury cup at M which rotates with the magnet, and from which a metal wire projects dipping into a fixed circular mercury trough K F by which connection is made to the battery. This arrangement, it will be noticed, permits of free rotation of the magnet.

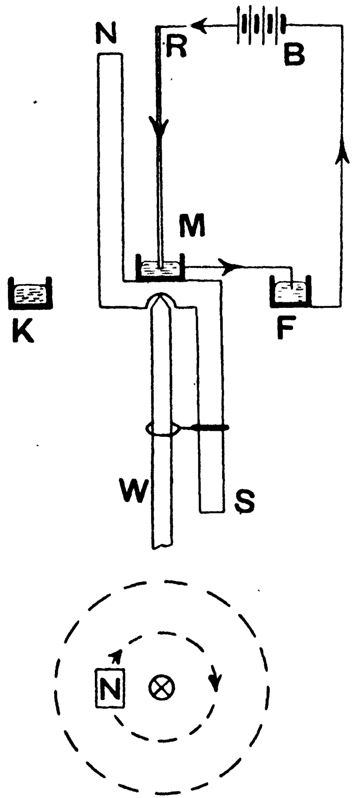


FIG. 16.

Suppose the arrangement is looked at vertically from above; the direction of rotation is shown by the arrowheads on the dotted circles. We see that it amounts to a single pole free to rotate in the magnetic field produced by the current, and from previous diagrams we see that it will rotate in a clockwise direction.

If it were a S pole it would move in the opposite direction; and further, a reversal of current would also effect a reversal in the direction of rotation.

From these ideas we see that a single magnetic pole in a magnetic field is acted upon by a mechanical force tending to move it along the lines of flux, and we have agreed to mark our lines of flux in the direction in which a free N pole would tend to move (see Figure 17).

These directions can always be called to mind by imagining a magnet to be placed near the conductor and applying the swimming rule to find which way it will set itself.

Another useful rule may be stated as follows :—

When the current is flowing inwards (i.e. away from us) the line of flux is to be marked in the direction in which a corkscrew would have to be rotated to make it enter the conductor, and when flowing outwards (i.e. towards us) the direction of

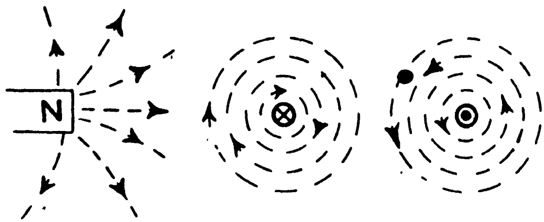


FIG. 17.

the line is that in which a corkscrew would have to be rotated to withdraw it from the conductor (see Figure 18).

Notice these marks do not mean that the line of flux is itself moving in the direction of the arrow, it is only the means of distinguishing between two sets of lines having different origins.

To illustrate further the usefulness of such diagrams, consider two conductors AB and CD (Figure 19) carrying currents

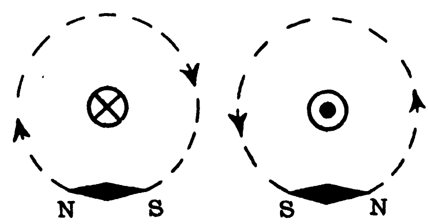


FIG. 18.

and placed parallel to each other : first suppose the currents are in opposite directions, then looked at end on from DB, the key diagram is as shown.

We see that the lines of flux are in the same direction between the conductors, and by the first property of lines of flux they repel each other sideways. Hence we infer that the conductors repel each other.

If the currents are in the same direction we get another key diagram showing the lines of flux in opposite directions between the conductors: now as a matter of fact we should be led to correct conclusions if we assumed the converse property to be true, and said that lines of flux in opposite directions attracted each other.

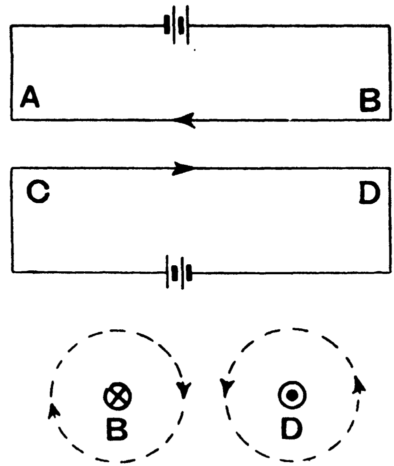


FIG. 19.

This however is not the best way of looking at the matter; it is better to regard two lines passing through the same space in opposite directions as neutralising each other, then we see that the field between the conductors will be weakened and the lines will tend to merge into one set as shown at B in Figure 20.

As, however, lines of flux tend to contract, the result will be as if the two conductors were surrounded by stretched elastic threads, whose contractile tendency pulls them together.

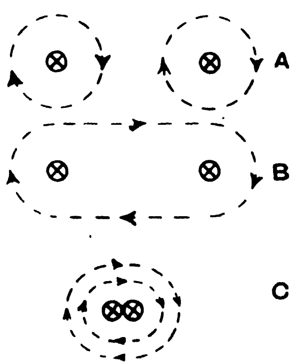


FIG. 20.

This means that parallel conductors carrying currents in the same direction attract each other; but we see that the actual forces are between the two sets of lines of flux and not between the conductors themselves.

These actions can of course be easily verified experimentally and are applied to useful purposes in many instruments, for instance in Wattmeters (see p. 390).

So far we have considered only straight conductors. Now let us suppose the wire to be wound

into a coil, and for convenience let it be a long hollow tube-like coil, usually termed a "solenoid."

If whilst a current is flowing through it we bring near it a compass needle, we find the solenoid simulates in quite a remarkable way the actions of a weak bar magnet: one end acts like a N pole and the other like a S pole, and these poles are reversed when the direction of the current is reversed.

Further, if we cut a piece of cardboard and place it so that

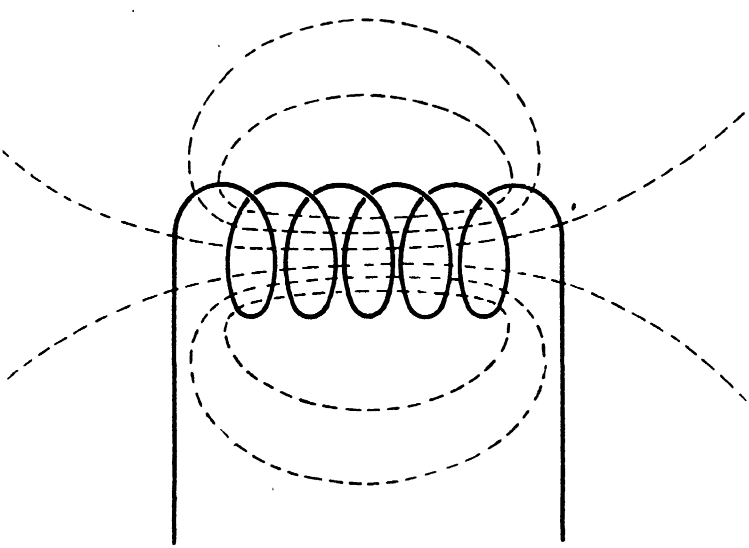


FIG. 21.

it may give us a longitudinal section of the coil, as shown in Figure 21, and scatter iron filings on it, we find that they readily arrange themselves in lines passing through the coil and returning outside; the pattern resembling that previously obtained with a bar magnet.

The relation between the direction of the current and the polarity is found to be as shown in Figure 22.

We see this relationship is given by the "swimming rule"; if we suppose the swimmer to keep his face towards the interior of the coil, the N pole will always be on his left hand. These

results are practically the same whatever the shape and size of the coil may be; for instance, a coil of one turn of wire carrying a current may be looked upon as a very short and wide magnet, one side being of N and the other of S polarity.

This magnetic effect of a coil is so important in practice

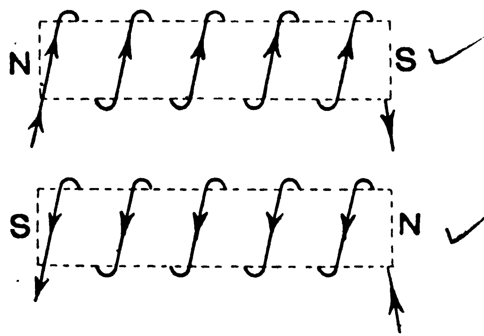


FIG. 22.

that it deserves further consideration: apparently it has no direct relationship to our fundamental fact that circular lines of flux surround a single straight conductor.

To show there is such a relation, we draw the coil in longitudinal section as in Figure 23, and assume that the circular distribution round the conductor holds good.

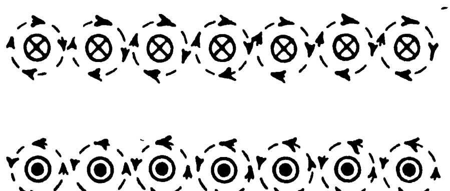


FIG. 23.

To avoid confusing the figure we show only one layer of the winding, and only one line of flux to represent the field due to each little piece of conductor. We see at once that inside and outside the coil all the lines run in the same direction, whereas between the conductors they are in opposite

directions. This means that the lines of flux neutralise each other between the conductors and strengthen each other elsewhere: this leads to the construction shown in Figure 24.

The form of the lines of flux thus obtained does not quite resemble the actual results obtained with filings, but we must remember that we are not dealing with one or two lines of flux, but with a magnetic effect that extends throughout space, and which can only be adequately represented by many such lines; and further, we must remember that one of their essential properties is that tendency to spread out which we have expressed by saying they repel each other sideways.

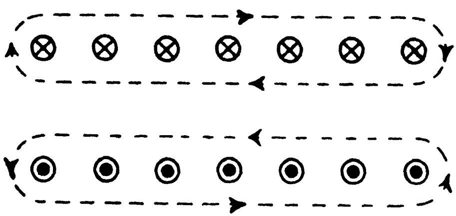


FIG. 24.

Such spreading is impossible inside the coil, but outside the coil it gives the actual distribution obtained in practice.

Our coil possesses another very important property; if an iron wire or rod be placed partly inside it, it is pulled strongly within the coil, the force on it being a maximum for some particular position, and decreasing to zero as it gets fairly inside the coil.

We may regard this action as an instance of property number 7 (page 11), the iron tending to set itself in the strongest part of the field, or so that as many lines of flux as possible pass through it: we shall meet many instances of its practical application (i.e. see arc-lamp mechanism).

The iron rod is also found to be magnetised; permanently, if of steel, or only while inside the coil and while the current is flowing, if of soft iron.

In fact if we fill up the space inside the solenoid with a soft iron rod, the magnetism produced is immensely stronger than that produced by the current in the coil alone. We can easily understand why this is the case, by noticing the behaviour of little compass needles placed inside a hollow coil; each tends

to set itself along the lines of flux and hence points axially along the coil.

Similarly the little atomic magnets of which we imagine the iron core to consist will all tend to set themselves axially along the lines of flux, and in so far as they succeed, they add their own magnetic lines to those already produced by the current.

By this means an enormous relative increase in the number of lines of flux is obtained, for the coil alone, even if carrying a fairly strong current, behaves like a very weak magnet.

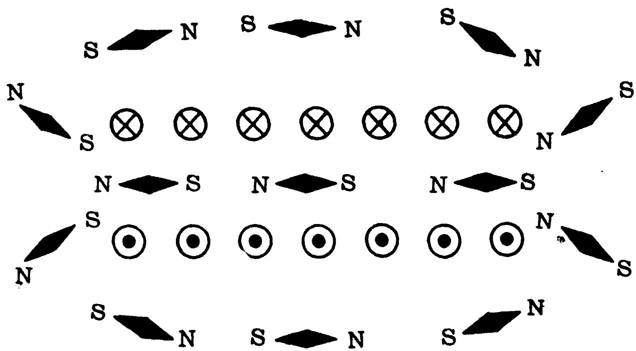


FIG. 25.

We thus obtain an "electro-magnet," a device which has many forms and is applied to innumerable purposes. Apart from the fact that it enables us readily to magnetise iron much more strongly than can be done by means of steel magnets, its practical use depends chiefly on the power it gives us of obtaining a mechanical pull, quickly acting, and easily controlled at a distance from the operator.

As regards the polarity of the iron, a glance at Figure 26 shows that it is the same as that of the coil itself and hence may be found by the swimming rule already given.

The subject of electro-magnets is so extensive that here we must limit ourselves to a short sketch of the principles and actions common to all types.

In the first place we must clearly distinguish between the magnetising force of the coil and the magnetic induction produced by it in the iron core.

The Magnetising Force, for a coil of fixed length, can be shown to be accurately proportional to the "ampere turns" or product of the strength of the current into the number of turns of wire; hence it can be increased without limit by increasing either the current, or the number of turns, or both. For instance, a coil of fifty turns, carrying a current of ten amperes, is said to have 50 × 10 or 500 ampere turns, and its effect on an iron core is identical with that due to another coil of the same shape and size, but having 500 turns and carrying one ampere, or having twenty turns and carrying twenty-five amperes, or any combination of current and turns provided the product is 500.

Now, the same magnetising force may produce very different "magnetic effects," thus it will produce a far greater effect (i.e. more lines) if the core of the solenoid is iron, than if it is air or other non-magnetic material; and again, a larger effect will be produced if the core is composed of iron of good magnetic quality, than if composed of iron of poor magnetic quality.

This effect, known as the "Magnetic Induction," produced in the core, is by no means proportional to the ampere turns; a complete statement cannot be given as yet, but in general terms we may say that as we uniformly increase the current in the coil (and thereby the ampere turns and magnetising force) from some small value, the magnetic induction produced in good soft iron at first increases slowly (this stage only lasts for a short time), then much more rapidly, and finally very slowly again; beyond this point any increase in the ampere turns produces very little extra magnetic induction in the iron, which is then said to be "saturated."

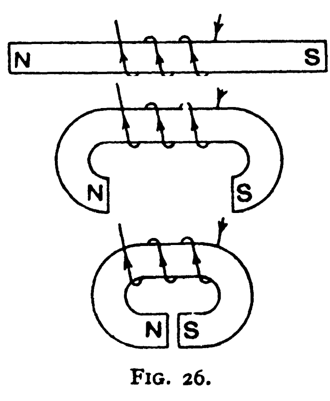


FIG. 26.

The degree of magnetisation at which saturation occurs varies very much with the quality of the iron; the purer and softer it is the more strongly it may be magnetised, any impurity usually reducing

the limit (there are exceptions; aluminium in certain proportion appears to improve the iron).

Remembering that the effect of the current is not to create magnetism, but only to arrange the direction of the molecules, and make them reveal the magnetism they already possess, such a limit to magnetisation is only what would be expected.

In the second place, we find that if we keep the current in the coil constant at some value less than that corresponding to saturation, the extent to which the iron is magnetised depends very much upon its shape.

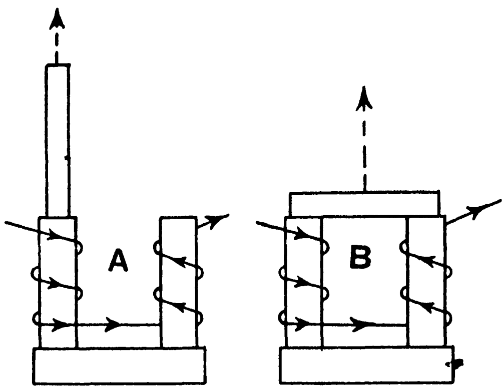


FIG. 27.

For suppose we start with a straight core and assume it to be gradually bent round until the ends meet as shown in Figure 26, then the number of lines of flux produced in the iron steadily increases until the ends meet, and a further increase would occur if we could weld them together.

The general truth of this statement may be roughly verified by testing with a spring-balance the pull of a horse-shoe electro-magnet on a soft iron keeper; A, when it touches one pole only; B, when it touches both at the same time (see Figure 27); the increase in the pull is enormous.

This effect gives a first conception of the idea of a magnetic circuit, which becomes of great importance later on. Generally speaking the better the *iron path* provided for the magnetic lines, and the less *air gap* we have, the greater will be the

magnetic induction or degree of magnetisation produced by a given number of ampere turns.

Thirdly, to a certain limited extent, it is immaterial how the winding is arranged and hence this is largely a matter of convenience.

In the instances shown in Figure 28, the controlling factors are the ampere turns, the length and section of the iron, and the length of the air gap ; if these are the same, the position of the winding is of minor importance.

Fourthly, we find that the amount of **residual magnetism** (i.e. the magnetism which remains after the current ceases) depends, like the magnetism itself, very much upon the shape of the iron.

No iron once magnetised completely loses the whole of its magnetism again, unless heated to redness or subjected to other special treatment ; but in the case of good soft iron in the form of a short straight bar the residual effect is quite small. As its shape approaches more nearly the form of a closed iron ring, so does the residual magnetism increase.

For instance, suppose we experiment with an ordinary horse-shoe magnet as at B, Figure 28 :—

Attach a soft iron keeper to a spring-balance, excite the magnet, break the circuit, then put the keeper on and measure the pull required to detach it ; it will be practically negligible.

Now place the keeper across the poles (keeper and poles not being especially smooth), pass the current for an instant, break circuit, and again try to detach the keeper ; the pull is now very marked.

Next let the surfaces of the poles and keeper be trued up and scraped until they make good contact ; on repeating operations, the keeper now sticks on very strongly indeed after breaking the circuit, and it requires great force to pull it off.

But once detached it will not stick again if replaced, because the residual magnetism has now decreased to its usual small amount at the moment of separation.

If we repeat the experiment, first putting a layer of paper or other non-magnetic material between keeper and poles, the residual effect is greatly weakened.

Hence we deduce the following general rule :—

If the lines of flux have much air path and little iron path, there is little residual magnetisation and vice versa.

Further, even a small air gap in an otherwise complete "magnetic circuit" largely reduces the residual magnetisation.

The influence of these factors on design may now be pointed out. If the magnet is merely required to attract a piece of iron in contact with it as strongly as possible the thicker and more complete the iron path the better, and its length need only be sufficient to allow room for winding.

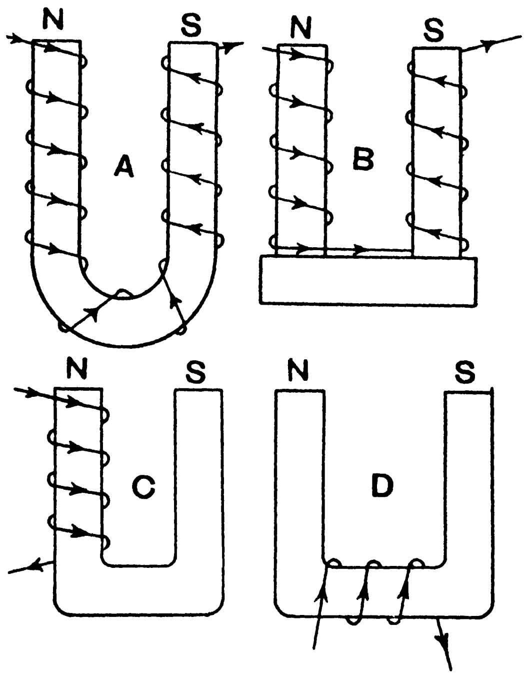


FIG. 28.

Any kind of air gap or a reduction in section of the iron anywhere would be highly prejudicial.

If the armature has to exert a certain moderate pull on an armature, and also has to work quickly, as in the case of an ordinary bell or a telegraphic instrument, then it must gain or lose its magnetism very quickly, and consequently the attracted armature must never touch the poles.

Such bells will work readily with quite a small current because of the tendency of successive feeble impulses to aid each other in setting up an increasing amplitude of vibration.

In fact, their natural period of vibration is small enough to enable them to work very well, as a rule, without a contact breaker with an alternating current of frequency fifty periods per second.

UNDER DOME TYPE

The action is exactly the same in this class of bell, but the working parts are concealed within the gong itself, thus giving neatness and compactness of design and security from injury.

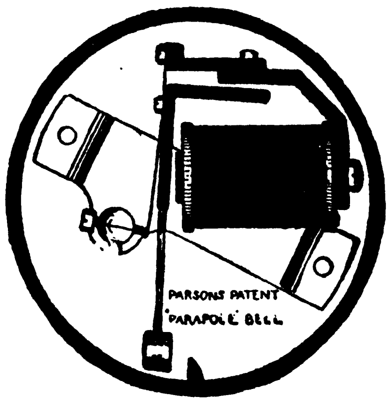


FIG. 30.

The ordinary construction is in this case unsatisfactory because the hammer shaft has to be curtailed to come within the dome, and the shortness of stroke involved means feeble ringing.

In Gent's "Parapole" movement (see Figure 30) the difficulty is surmounted in an ingenious manner, and by a due attention to the principles of the magnetic circuit, a very compact but powerful one-core type of electro-magnet and armature has been produced.

If in the ordinary type of bell a single core or bar electro-magnet were used, in order to save room, the return path of

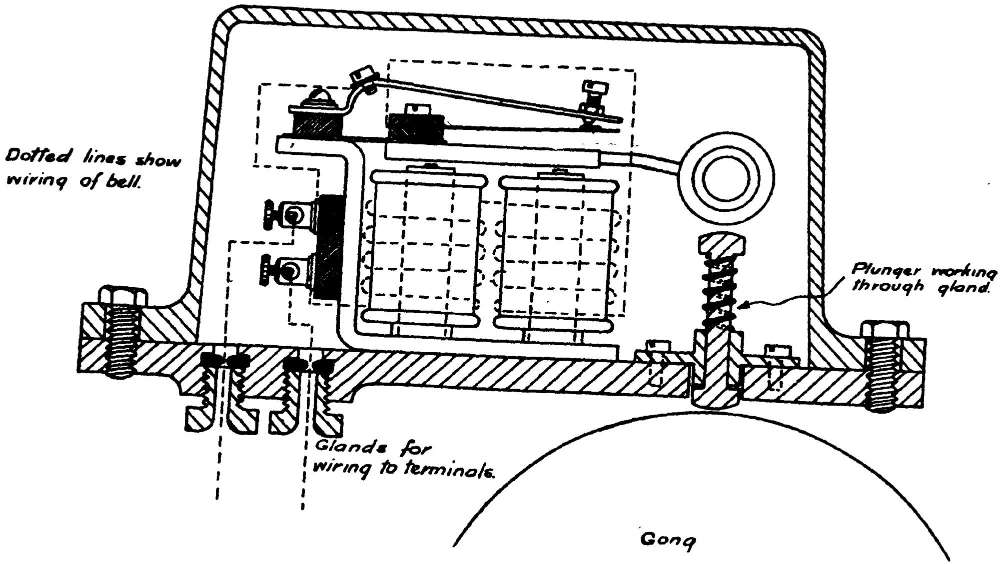

Dotted lines show
wiring of bell.
Plunger working
through gland.
Glands for
wiring to terminals.
Gong

FIG. 31.

the magnetic lines would be mainly through the air, and as already stated the magnetic effect obtained would be very much feebler, with a given number of ampere turns, on this account alone.

In this case the magnetic circuit is completed through the bent armature with only two small air gaps, and the " magnetic pull " is exerted at the two ends in a very efficient way, while at the same time nearly the full diameter of gong is utilised for the stroke.

AIR-TIGHT BELLS

Sometimes, as in mines and in damp situations, an absolutely air and water-tight bell is required.

Figure 31 shows how this may be obtained.

The bell movement is completely enclosed in an iron case, and the stroke of the hammer is conveyed to the gong by means of a separate plunger, working through an air and water-tight gland. Two similar glands are provided for the leading in wires. The bell itself is of the usual type, excepting that the contact breaker is more carefully made, being designed to give a powerful stroke and to work for long periods without attention.

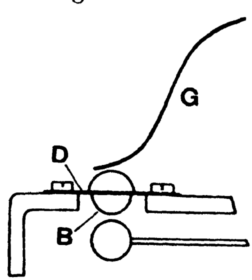


FIG. 32.

Messrs. Heyes & Co., of Wigan, make an especially interesting variety of water-tight mining bell, either single stroke or trembling. The movement is of the usual type, and is enclosed in a metal case on the outside of which is fixed the gong.

Instead of the hammer striking the gong as usual, it strikes a brass ball B mounted on a brass diaphragm D, screwed into the case as shown. The gong G is almost but not quite touching the ball. The diaphragm is quite a small one, as it is not required to act as a yielding spring, the ball itself transmitting the blow from hammer to gong.

It is an application of a well-known experiment in which a ball rolling down an inclined plane until it strikes a row of stationary balls drives off the furthest one without disturbing the others.

CONTINUOUS RINGING BELLS

The bells mentioned thus far only ring while the line circuit is completed, i.e. while the "push" is held down; but it is often desirable, for calling attendants or for ringing up firemen from headquarters, to use a bell which once started shall

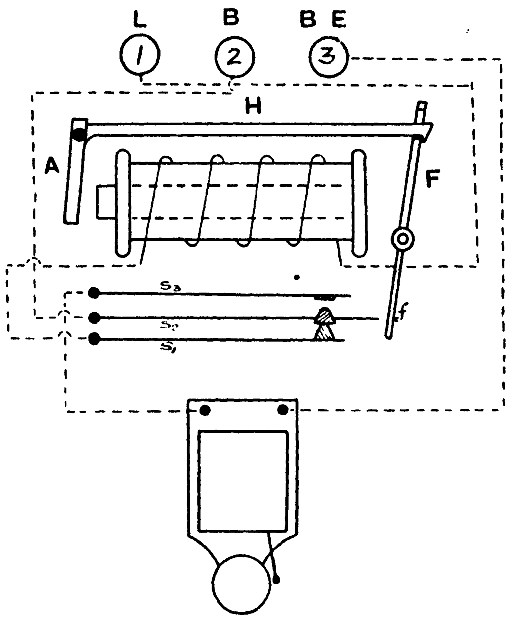


FIG. 33.

continue ringing until it has served its purpose by securing attention and replacement.

Some contrivance in the nature of a "relay" is necessary to close the circuit of the battery on the bell when the "push" is pressed; in the old type of continuous ringing bell a simple spring arrangement served the purpose.

This has been largely superseded by forms having a separate relay combined with an indicator which shows at once, amongst a number of bells, which is the one which requires attention.

Figure 33 shows one such device. Externally it resembles

an ordinary bell with a slightly larger cover than usual, which carries the indicator flap.

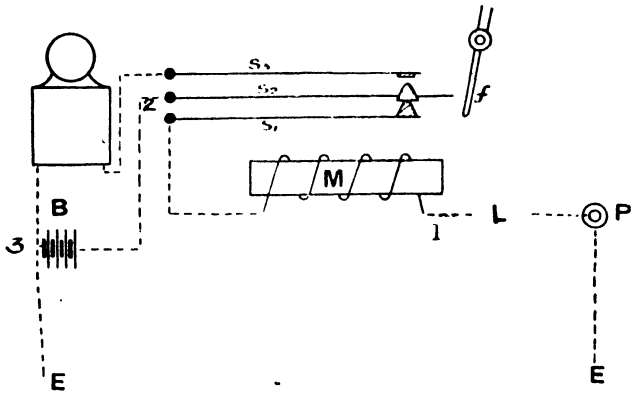


FIG. 34.

Inside there is the usual bell movement, and in addition a small horseshoe electro-magnet (the actual arrangement is simplified in the diagram, and the bell itself shown conventionally) with a pivoted armature A carrying a light brass bar H, which holds up the indicator flap F as shown; this has an extension *f* which, when the attracted armature releases its hold and the flap falls, catches up the prolongation of the spring contact S_2, and changes the internal connections, so that S_2 breaks contact with S_1 and makes contact with S_3, thus breaking the line circuit and completing the local circuit; the bell then rings and continues to do so until the indicator is replaced or the battery is exhausted.

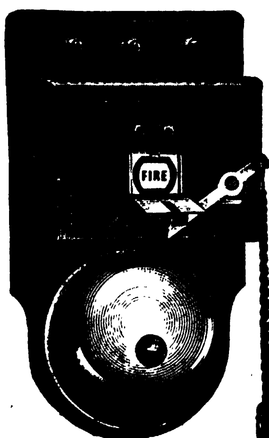


FIG. 35.

The relation of the indicator to the line circuit will be more clearly seen in Figure 34.

In this diagram the indicator magnet M is shown conventionally in order to avoid crossing of connections.

It will be seen that the bell is on open circuit until the push is closed; this enables a current to flow through the indicator-magnet, and the flap falls over until in its new position the battery circuit is completed as previously mentioned.

L is the line, P the distant push, and EE the earth connections or the return line as the case may be; (1), (2), and (3) indicate the position of the terminals corresponding to the previous figure.

An external view of this bell with the flap down is given in Figure 35.

SINGLE STROKE BELL

These are convenient when distinct signals have to be given as in railway work or mining; each press of the push or key produces one stroke only, and evidently no contact breaker is required, the current flowing through the magnet

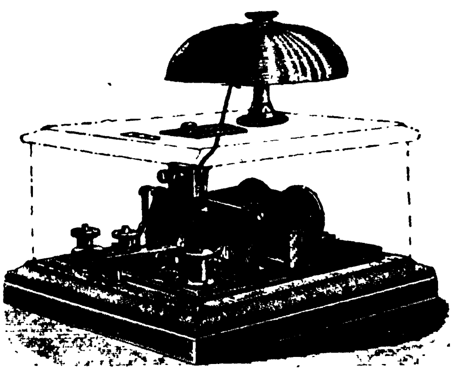


FIG. 36.

coils and moving the armature as soon as the circuit is closed, and holding it in its new position until the circuit is broken by releasing the push.

Such bells are characterised by a larger and more massive construction than the ordinary trembling bells, as there is NO gradual accumulation of weak impulses until a considerable

amplitude of swing is obtained, and each single impulse must therefore be strong enough to give a sufficiently powerful blow: hence armature and hammer are heavier and the length of the stroke considerable.

It is also important that the stroke should end before the hammer actually strikes the gong, otherwise it would, by being held there, tend to damp the vibrations.

The elasticity of the shaft then permits the hammer to swing slightly forward and strike the gong, but instantly it swings clear again.

Figure 36 shows a good form of a single stroke bell, the horizontal armature swings on screw pivots, and carries a massive hammer whose travel is limited by screws as shown.

The bell shown is also fitted with a "Morse Key" so that signals may be given as well as received, although this is not a necessary part of the bell.

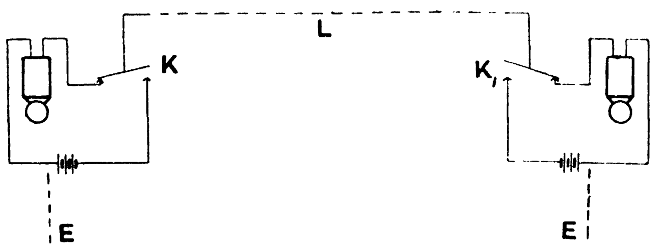


FIG. 37.

A Morse Key is a simple rocking lever which forms a very convenient two-way switch.

In practice the arrangements for sending and receiving signals from either of two distinct stations, would be as shown in Figure 37, where K and K_1 are the two keys, L the line, and EE, the earth connections or return line.

RELAYS.—A relay is a device for controlling a local circuit from a distance. If bells are required to be worked at the end of a long line, excessive battery power will be required if connected up in the usual way; it is then less expensive to insert a relay between the line and bell. A weak line current serves to actuate the relay, and this closes the circuit of a

local battery on the bell, which is just as much under control as if worked directly. In telegraphy relays are largely used in long distance transmission of messages, and as they must be exceedingly reliable and extremely rapid in action, their design becomes an important problem and they are made with the delicacy of a watch.

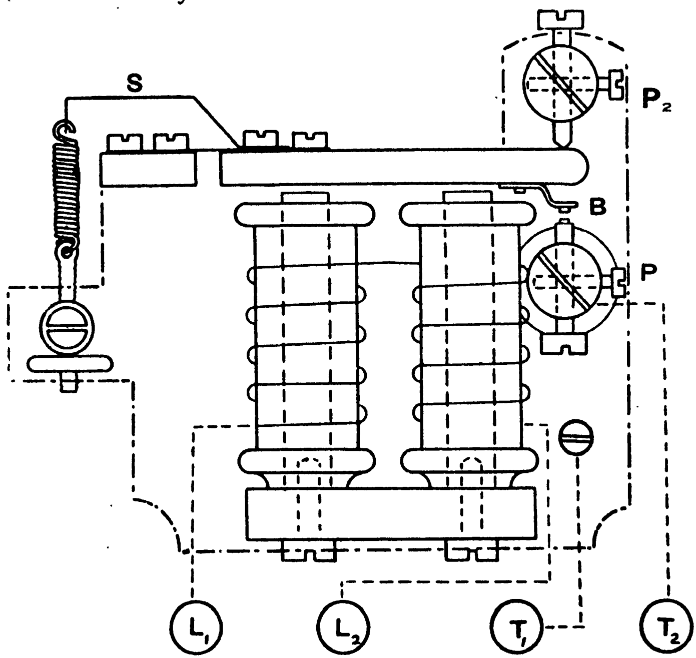


FIG. 38.

For ordinary bell work the conditions are much less onerous and a very simple construction is sufficient.

Such a relay is shown in Figure 38.

It resembles an ordinary bell movement, the coils of the electro-magnet being in circuit with the line.

One wire of the local circuit is connected, through T_1 to the brass casting which serves as a mount, and the other to an insulated pillar with a contact screw P.

When the armature is attracted, it closes the local circuit

at B, the current flowing from T_1 through the brass, the armature, the contact at B, and thence through P to T_2. P_2 is a dummy pillar which merely serves as a stop to limit the range of motion of the armature. The spring S serves to adjust the sensitiveness of the armature, L_1 and L_2 are the line terminals, and the chain line shown in the figure represents the outline of the brass base.

BELLS FOR USE WITH MAGNETO GENERATORS

Instead of using a relay and a local battery, a magneto generator (see page 126) may be used in some cases with advantage.

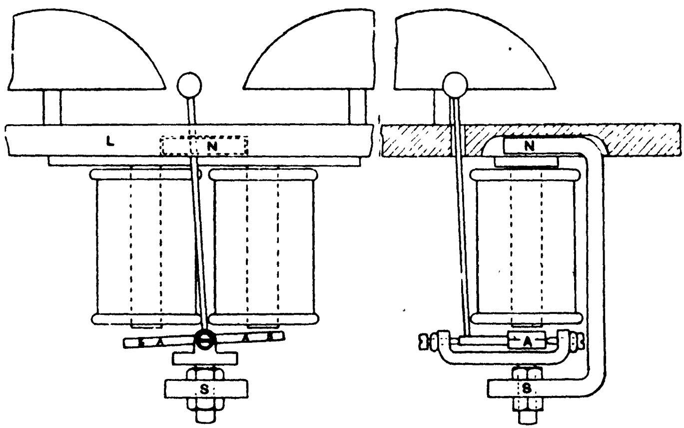


FIG. 39.

The call bell for telephones is often worked in this way. The generator may be wound for any desired voltage to suit various lengths of line, but in order to secure the utmost simplicity in construction and hence to reduce to a minimum the possibility of failure, it is necessary to arrange it to give alternating currents; consequently a type of bell adapted to work with such currents has been evolved.

This is shown in Figure 39. An inverted horseshoe magnet is fixed under the lid L of the enclosing box, outside of which are the two gongs; A is a pivoted soft iron armature, which can oscillate backwards and forwards as shown, and a bent

permanent magnet NS embraces the whole. In the earliest forms of the bell this magnet was dispensed with, and the armature itself was a steel magnet with consequent poles, i.e. both ends might be S poles and the middle a N pole of double strength.

Then when a current from the line passed through the

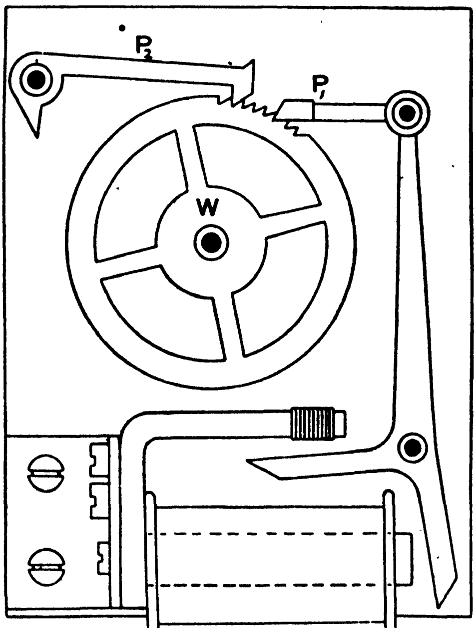


FIG. 40.

coils of the electro-magnet, making its poles N and S respectively, evidently one end of the armature would be attracted and the other repelled, and if the current were steady the armature would remain fixed in one position ; but the current is alternating, and as it reverses its direction the polarity of the electro-magnet also reverses, and the end of the armature which was previously attracted is repelled and vice versa. In this way a continuous oscillation is maintained, but such oscillations would gradually weaken the magnetism

in the armature and enfeeble the working of the bell, and therefore it is a very great improvement to make the armature of soft iron and magnetise it in the required way, with like poles at the ends, by induction from the fixed steel magnet which can be made fairly strong, and which is unaffected by the vibration.

ELECTRIC CLOCK MOVEMENT

As a final instance of the application of electro-magnets we may examine a movement which occurs in certain clocks which are governed electrically by a master clock.

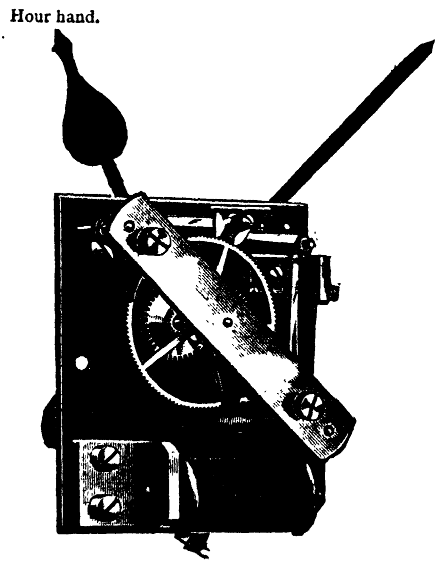


FIG. 41.

These are becoming largely used in factories, etc., and the ordinary mechanism is entirely dispensed with, the two hands being driven by an electro-magnetic arrangement which receives an impulse at regular intervals determined by a standard pendulum, which may be at any distance and which may govern any number of clock dials, whose indications must of necessity be in exact agreement.

Figures 40 and 41 show the driving mechanism used in Gent s form: W is a ratchet wheel with 120 teeth, P_1 P_2 are pawls with hard steel edges, one of which, P_1, is connected to the armature of a "parapole" electro-magnet.

Every half minute the standard pendulum sends a current along the line which draws back P_1 for an instant, and as it returns it drives the ratchet wheel round one notch, P_2 checking any reverse motion. This wheel carries the minute hand, and is also geared into a train of wheels with a 12 to 1 ratio which drive the hour hand. The motion is almost absolutely silent, and the arrangement is very simple and reliable.

The pendulum is itself driven by a device similar in principle, no winding is required, and the whole arrangement will work without attention for months. When in course of time the battery becomes weak, an automatic signal is given on a warning bell at half-minute intervals.

CHAPTER III

THE ELECTRIC CIRCUIT

AT the outset we may obtain some very useful ideas by supposing we are in a room supplied with gas and water, also with a connection to electric mains, so that we can obtain a current of electricity as we do gas or water without troubling ourselves with questions as to its origin.

If we turn on a gas tap a current of gas flows from the pipe, and we might agree to measure the strength of that current by the amount of gas which escapes per second. In order that the gas shall flow, there must needs be a pressure upon it before the tap was opened, and this may be of any value whatever; for instance, it will be very much greater in the case of water, although our general reasoning also applies in this case.

The presence of an initial pressure is absolutely essential; we might have any amount of gas in store, but merely opening the tap in the absence of pressure would produce so little effect that for present purposes we may neglect it.

Again the current strength is determined not only by the value of the pressure, but also by the size of the pipe connecting our tap with the large supply main in the street; if this is long and also small in diameter, ordinary experience tells us that we cannot get a very rapid flow of gas; this is because the pressure at the gas jet is less than the pressure in the street by an extent that depends upon what we call the "resistance" offered to the flow by the friction of the gas against the walls of the pipe.

We infer that although the essential thing we want is a current of gas, its strength is determined entirely by the pressure upon it in the mains, and upon the length and diameter of the pipe which conveys it from the mains.

This means that at the gasworks the engineers do not worry themselves directly about the quantity of gas they must supply; what they do is to keep the pressure constant and then the current looks after itself, the first effect of an increased demand being a fall in pressure, which is at once indicated by their gauges.

It is most important to notice that although we can have a pressure without a current (as when gas is turned off), yet we cannot possibly have a current without a pressure. In applying these ideas to the case of an electric current, the first great difference we notice is that now we require two terminals or taps, to which we must attach respectively the two ends of the conductor through which we wish our current to flow.

It is as if our gas came to the burner by one pipe and returned from it by another, and we express this by saying that a current of electricity flows in a closed circuit. In other respects the above argument applies very well to the electric circuit.

Notice that the two metal bolts or terminals, which are connected to the two underground conductors in the street, *must* be in some peculiar state *before* we connect our conductor to them; this we express by saying that there is a **Difference of Potential** between them, and by a commonly accepted usage we write this P.D., as an abbreviation for "Potential Difference."[1]

This P.D. is not the current, for it exists whether we have a current or not; it bears the same relation to an electric current as the gas pressure does to the current of gas, and it is also important to realise in the electrical case that we cannot have a current without a P.D., though of course we can have a P.D. without a current.

And again it is the business of the engineers at the generating station to keep this electrical difference of pressure constant; if they do that every consumer obtains the correct strength of current.

If now we connect wires of the same metal, but of different

[1] It is quite unnecessary here to discuss the physical meaning of this statement; students will eventually realise that the terminals carry small electric charges and are connected by "lines of electric force" (see p. 383).

lengths and sections, to the supply mains, we find the current through them varies much in the same way as does the current of gas in a pipe: the longer and thinner the wire the smaller the current and vice versa. Hence we speak of the wires as possessing **Resistance**, and regard the current through them as being jointly determined by the P.D. between their ends and this resistance.

The three terms used above in connection with the electric circuit must be defined in some way that will admit of their measurement in terms of suitable units: how these units have been obtained and the theory connecting them will partly appear as we go on. Meanwhile it is sufficient for our purpose to make the following statements:—

1. Electric difference of pressure or Difference of Potential is measured in **Volts**, and hence is frequently referred to as the "voltage."

2. Current strength is measured in **Amperes**.

3. The Resistance of a conductor is measured in **Ohms.**

We shall assume that we are provided with instruments known as "Voltmeters" and "Amperemeters" or "Ammeters" by which we can measure voltage and current. At present we need not concern ourselves as to how they work.

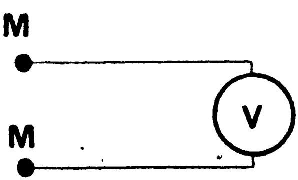


FIG. 42.

If we connect a voltmeter up to the supply mains as in Figure 42, it indicates or shows on its scale the voltage of the supply, i.e. the P.D. across the mains, say 100 volts.

If we connect an ammeter in the same way it will probably be "burnt out" at once by a sudden rush of current owing to its having a very low resistance.

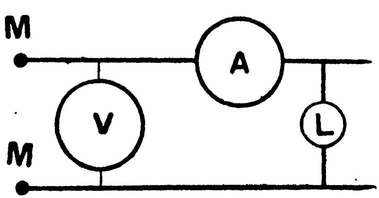


FIG. 43.

Suppose we connect up to the mains an incandescent lamp intended to work at 100 volts and arrange the instruments as

shown in Figure 43, where L is the lamp, V the voltmeter, A the ammeter, and MM the mains.

The lamp filament is a conductor of rather high resistance, and the voltmeter indicates the P.D. between its ends, whilst the ammeter indicates the current flowing through it. We note the readings, and for a 60-watt lamp we may get say 100 volts and 0·6 ampere.

Now arrange an exactly similar lamp in series with the first as in Figure 44.

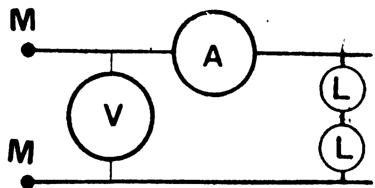


FIG. 44.

The voltmeter shows the same reading as before, but the ammeter only shows a half of its previous reading. This shows that by doubling the resistance (by doubling the length of the filament) and keeping the P.D. the same, we halve the current.

If we apply the voltmeter to each lamp in turn we shall find the P.D. across each is 50 volts. That is, if we keep the resistance unchanged but halve the voltage we halve the current.

Such measurements illustrate what is known as **Ohm's Law**, which states that

the current in any circuit, or any part of a circuit, is directly proportional to the voltage acting in that circuit, or part of a circuit, and inversely proportional to the resistance.

Using the ordinary units this may be expressed in the form—

$$\text{Current in Amperes} = \frac{\text{Potential Difference in Volts}}{\text{Resistance in Ohms}}.$$

These experiments also illustrate the use and action of the instruments used. An ammeter has a very low resistance, the lower the better, and is placed in the circuit so that the current to be measured passes through it. A voltmeter has, or should have, a very high resistance, the higher the better, and is always connected to the two points between which the P.D. is to be measured, and for most purposes we may disregard the current it takes.

It must be understood that, as a rule, such instruments are not intended to be used for very exact measurements; we must regard them as giving, easily and quickly, results which are approximately true.

We have now to define more carefully the meaning to be attached to certain terms in frequent use.

So far we have only considered the mains to which we have access, but evidently our lamps connected to them form part of a much larger circuit: in all cases we may

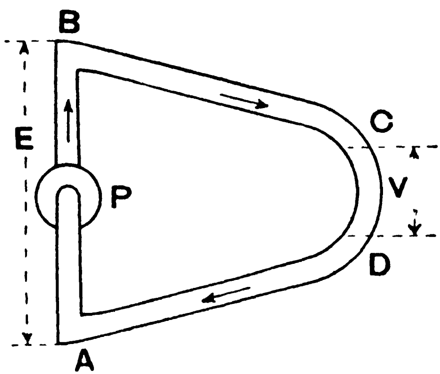


FIG. 45.

consider a current to flow in a closed path in which somewhere there is a "generator," which may be a battery, dynamo, or thermo-generator, etc.

In this is generated a certain "electric pressure" or "voltage," in virtue of which the current flows.

It is much as if we have a pump at work, pumping up water from a point A (see Figure 45) until it reaches a maximum height B, from which it can fall down again by gravity to its old level, to be again pumped up to B.

Here AB represents the inside of the generator and BCDA the external circuit.

Without further detail, which would obscure the matter unnecessarily, the analogue is not quite exact; but we can at any rate see that the pump produces a certain maximum pressure or difference of level, roughly measured by the height AB.

In the case of an electrical circuit we may regard the total voltage produced as a constant quantity for a given battery or dynamo working steadily, and we call it the total "Electromotive Force," or more generally the E.M.F., and denote it by the capital letter E; it is of course measured in volts, and may be more exactly defined as the difference of electrical potential between the poles of the generator when the latter is sending no current.[1]

In many cases, however, we do not need to consider the whole circuit but only a part of it as from C to D (Figure 45). Then we need only think of the difference of electrical level between C and D as measured by a voltmeter connected between these two points: this is also measured in volts and is evidently a portion of the total E.M.F., E.

We might speak of it as the "E.M.F. between C and D," but to avoid confusion we shall reserve the term E.M.F. and the letter E to denote the total voltage in the whole circuit, and shall speak of the "P.D." between C and D, and denote it by the letter "V," frequently defining it more particularly by some suitable affix.

We shall also generally use a capital letter R as a symbol for the resistance of a circuit though a suitable affix will sometimes be employed to denote a particular part of the total resistance of a circuit.

Unless the circuit divides into two or more branches the current is the same all the way round the circuit, and there is in consequence not the same danger of confusion.

We may again point out that Ohm's Law may be applied to a whole circuit or to any part of a circuit; for instance, if we connect a wire of 10 ohms resistance to mains kept at 100 volts, our ammeter will show that 10 amperes is passing through the circuit and we have

$$I = \frac{V}{R} = \frac{100}{10} = 10 \text{ amperes.}$$

Writing this formula in the form $V=IR$, we see it means that to send a current of I amperes through R ohms requires a P.D. of IR volts.

[1] As a matter of fact the difference of potential between the terminals of a generator usually falls when current is taken from it, and it will appear later that this quantity is not to be confused with the E.M.F. when the generator is working on load (see pp. 70 and 146).

Here we are dealing with a portion of a larger circuit, and this is all we require at first; if, however, we know the resistance of the whole circuit R, and the total E.M.F. in it, we may write

$$E = IR.$$

Ohm's Law is further discussed in chapter IV.

Returning to the experiment already mentioned, we see that if 100 volts sends 0·6 ampere through a certain lamp, it means we have

$$100 = 0{\cdot}6R, \text{ or } R = \frac{100}{0{\cdot}6} = 167 \text{ ohms (nearly)}.$$

That is, the resistance of the lamp filament is 167 ohms.

Hence the resistance of any lamp or conductor can be measured, approximately at any rate, by measuring the current through it and the P.D. across it by means of an ammeter and voltmeter.

When we put two lamps in series and connected the voltmeter across them both we obtained readings of 100 volts and 0·3 ampere.

Here $V = IR$, where R now stands for the resistance of two lamps in series.

$$\therefore 100 = 0{\cdot}3R, \text{ or } R = \frac{100}{0{\cdot}3} = 334 \text{ ohms (nearly)}.$$

Again, if the voltmeter read 50 volts across each of them, and if R=167 ohms, the current through it should be

$$I = \frac{V}{R} = \frac{50}{167} = 0{\cdot}3 \text{ ampere}.$$

In this latter case we observed the lamps gave very little light.

Now we connect up as shown in Figure 46, so that each lamp forms an independent connection across the mains: the lamps are said to be in "in parallel."

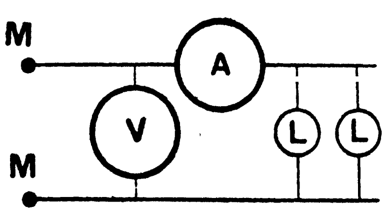


FIG. 46.

The voltmeter reads 100 volts, which is the voltage on each lamp, and the ammeter reads 1·2 amperes.

Hence if R now stands for the resistance of the two lamps in parallel taken together we have

$$V = IR \therefore 100 = 1{\cdot}2\ R, \text{ or } R = \frac{100}{1{\cdot}2} = 83 \text{ ohms (nearly).}$$

That is, the resistance of the two lamps in parallel is half that of one of them.

Or we may consider them independently, and then we see that each obtains its proper current of 0·6 ampere without interfering with the other.

Summing up our results, we see that if we put n lamps, each of resistance R ohms, in series, the total resistance is $n \times R$ ohms; and if we put them in parallel it will be $\frac{1}{n} \times R$ ohms.

Example.—It is required to run 500 100-volt lamps, each having a resistance, when hot, of 182 ohms. Calculate the current and voltage required (*a*) when they are placed in series, and (*b*) when they are placed in parallel.

(*a*) When the lamps are placed in series, the voltage will have to be $500 \times 100 = 50{,}000$ volts, and as the combined resistance is $n \times R$ or 500×182 ohms, the current will be $\frac{V}{R} = \frac{500 \times 100}{500 \times 182} = 0{\cdot}55$ ampere.

$\therefore$ when the lamps are in series a current of 0·55 ampere at a voltage of 50,000 will be required.

(*b*) When the lamps are in parallel the voltage will be 100, the same as for one lamp. The combined resistance of 500 lamps will be $\frac{R}{n}$, or $\frac{182}{500}$, that is, 0·364 ohm.

The total current $= \frac{V}{R} = \frac{100}{0{\cdot}364} = 275$ amperes.

Or it is equally correct to say that the current through each lamp $= \frac{V}{R} = \frac{100}{182} = 0{\cdot}55$ ampere, and therefore the total current will be $500 \times 0{\cdot}55 = 275$ amperes.

When the lamps are in parallel, therefore, a current of 275 amperes at a pressure of 100 volts is required.

The first case is not practical on account of the difficulty and danger introduced by high voltages, and the result shows that such lamps are only adapted for working in parallel.

The following examples are chosen to illustrate the ease and flexibility with which Ohm's Law can be applied to somewhat

more complicated cases and are also designed to clear up difficulties which are of common occurrence.

Example.—Resistances of 4 and 8 ohms are connected in series and placed across the terminals of a battery whose E.M.F. and internal resistance are 8 volts and 0·5 ohm respectively. Calculate the current flowing round the circuit, the voltage drop across each resistance and the P.D. of the battery.

Since the current has the same value in all parts of the circuit the law may first be applied to the entire circuit and we have

$$I=\frac{E}{R}=\frac{8}{4+8+0\cdot 5}=\frac{8}{12\cdot 5}=0\cdot 64 \text{ ampere.}$$

Voltage drop across the 8 ohm resistance $=0\cdot 64 \times 8=5\cdot 12$ volts.
Voltage drop across the 4 ohm resistance $=0\cdot 64 \times 4=2\cdot 56$ volts.
The P.D. of the battery may be found by determining the voltage drop across the entire external resistance and is $0\cdot 64 \times 12=7\cdot 68$ volts. An alternative method for determining the P.D. of the battery is to determine the voltage drop inside the battery and subtract this amount from the E.M.F. of the battery, thus:

$$\text{P.D. of battery}=8-0\cdot 64 \times 0\cdot 5=7\cdot 68 \text{ volts.}$$

This voltage is, of course, the value which would be indicated by a voltmeter connected across the battery when sending the current found above.

Example.—A battery of 126 accumulators, each having an E.M.F. of 2·05 volts and an internal resistance of 0·01 ohm, is placed in series with a resistance of 1 ohm and connected, for charging purposes, to a dynamo having an E.M.F. of 300 volts and an internal resistance of 0·2 ohm. Calculate the magnitude of the charging current and the P.D. across each cell during charge. If the battery is afterwards discharged with a current of 20 amperes what will be the P.D. per cell?

In this case there are two E.M.Fs. in the circuit and they are in opposite directions, that of the dynamo being the greater. The current is found by dividing the resultant E.M.F. (the difference of the two opposing E.M.Fs.) by the total resistance.

$$\text{Charging current}=\frac{300-126 \times 2\cdot 05}{126 \times 0\cdot 01+1+0\cdot 2}=\frac{41\cdot 7}{2\cdot 46}=16\cdot 95 \text{ amperes.}$$

During charge the P.D. applied to each cell must be sufficient to neutralise the E.M.F. of the cell and, in addition, to drive the current through the internal resistance of the cell; it is therefore larger than the E.M.F. of the cell and in this case is equal to $2\cdot 05+16\cdot 95 \times \cdot 01=2\cdot 2195$ volts.

It is worthy of note that a similar state of affairs exists when a D.C. motor is in operation, the P.D. applied to the armature circuit being larger than the back E.M.F. of the machine.

During discharge the P.D. will be less than the E.M.F. (since part of the E.M.F. will be used in sending current through the internal resistance of the cell) and will be equal to $2{\cdot}05 - 20 \times {\cdot}01 = 1{\cdot}85$ volt.

USE OF KIRCHHOFF'S LAWS

When the resistances forming a circuit are in simple series connection or in simple parallel connection, problems of current flow can usually be solved on the lines indicated in the above examples combined with a knowledge of the law giving the equivalent resistance of a number of resistances in parallel (see page 59), but more complicated arrangements of resistances sometimes occur (they are often referred to as networks), and in such cases the best method of solution is to employ Kirchhoff's Laws, of which the first is very simple and the second may be regarded as an extension of Ohm's Law.

To go deeply into the use of these laws, though they form very important weapons whose value is not always appreciated, is beyond the scope of this book, but it is important that they should be known and their mode of application to simple problems explained. The use of Kirchhoff's Laws is also of importance when more than one E.M.F. is present in a network.

KIRCHHOFF'S FIRST LAW.—When several conductors meet at any point in a network, the sum of the currents flowing to the point is equal to the sum of the currents flowing away from the point.

KIRCHHOFF'S SECOND LAW.—In any closed circuit in a network of conductors, the sum of the products of the resistance of each conductor into the current flowing through the conductor is equal to the E.M.F. in that closed circuit.

The procedure to be adopted when applying these laws to a problem is as follows :—

1. Make a diagram of the circuit and place an arrow on each conductor to indicate what we may call the positive direction of current in that conductor. Observe that the arrow does not necessarily indicate the actual direction of current in the conductor (which is not known at this stage of the

proceedings), and if the current, when found, is prefixed by a negative sign, it means that the direction of current is opposed to the arrow shown on that particular conductor.

2. Label the current in each conductor with a suitable symbol, using as few independent symbols as possible. It will be found that judicious use of the First Law enables the number of independent symbols to be kept to a minimum.

3. Using Kirchhoff's Second Law, write down the appropriate equation for any closed circuit in the network. Repeat this for other closed circuits until a number of equations equal to the number of independent unknown currents is obtained.

4. Solve these equations simultaneously and the several currents will be obtained.

Example.—A cell A having an E.M.F. of 1·4 volt and an internal resistance of 0·6 ohm is connected in parallel with a cell B having an E.M.F. of 1·1 volt and an internal resistance of 0·2 ohm, and the combination is used to send current through an external resistance of 2 ohms. Calculate the current sent by each cell if the resistance of the connecting wires be neglected.

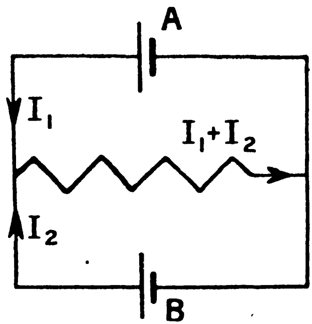


FIG. 47.

The circuit is indicated in Figure 47 and arrows to indicate the positive direction of current in each conductor are shown. If the currents sent by cells A and B are called I_1 and I_2 respectively, it is clear, by Kirchhoff's First Law, that the current through the resistance will be I_1+I_2. Applying the Second Law to the closed circuit composed of the cell A and the resistance we have

$$I_1 \times 0{\cdot}6 + (I_1+I_2)2 = 1{\cdot}4$$
$$\text{or } 2{\cdot}6I_1 + 2I_2 = 1{\cdot}4. \quad (1)$$

Applying the same law to the circuit composed of the cell B and the resistance we have

$$I_2 \times 0{\cdot}2 + (I_1+I_2)2 = 1{\cdot}1$$
$$\text{or } 2I_1 + 2{\cdot}2I_2 = 1{\cdot}1. \quad (2)$$

From (1) $5{\cdot}2I_1 + 4I_2 = 2{\cdot}8$ and
from (2) $5{\cdot}2I_1 + 5{\cdot}72I_2 = 2{\cdot}86$.

Subtracting $-1{\cdot}72I_2 \doteq -{\cdot}06$ whence $I_2 = 0{\cdot}03489$ amp., and, since it is positive, the current is in the direction of the arrow. Substituting for I_2 in (1) we have

$$2{\cdot}6I_1 + 0{\cdot}06978 = 1{\cdot}4$$

$$\therefore \quad I_1 = \frac{1{\cdot}33022}{2{\cdot}6} = 0{\cdot}5117 \text{ amp.}$$

This current will also be in the direction of the arrow shown in the diagram.

The P.D. across the external resistance may be found by three alternative calculations (see example on page 48), and each method will be found to give a value of 1·093 volt.

Example.—Calculate the current through each member of the network shown in Figure 48 when a cell having an E.M.F. of 2 volts and of negligible internal resistance is placed across the points A and B. What is the equivalent resistance between the points A and B ?

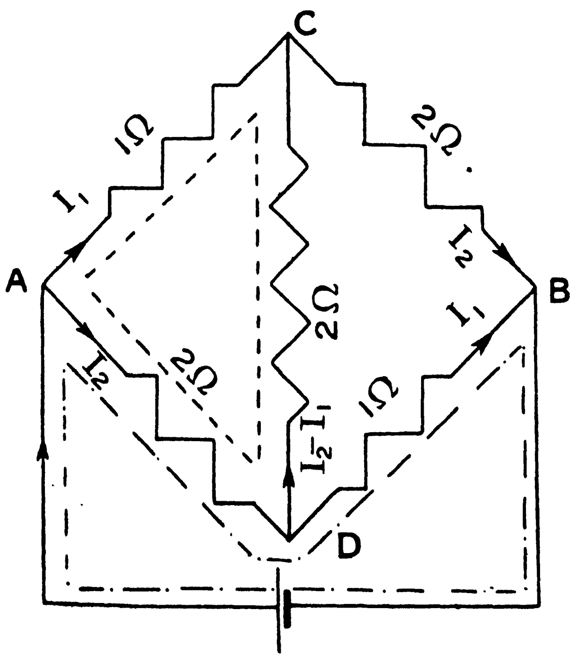


FIG. 48.

Let the currents in AC and AD be I_1 and I_2 respectively, then, since the circuit has been chosen with a certain symmetry in order to simplify the problem, the currents in DB and CB are I_1 and I_2 as indicated in the Figure. The current in DC will be $I_2 - I_1$ by Kirchhoff's First Law.

Observe that if the circuit had not been symmetrically arranged, the problem would still have been solvable, but three unknown currents would have been needed, making three equations necessary, and adding to the laboriousness of the example.

In the closed circuit indicated by the dotted line we have

$$I_1 \times 1 - (I_2 - I_1)2 - I_2 \times 2 = 0.$$

The negative signs for the second and third terms on the left-hand side of the equation are inserted because in going round the closed circuit we are moving against the arrows in the corresponding conductors. The right-hand side is taken as zero because there is no E.M.F. in this particular closed circuit. This reduces to

$$3I_1 - 4I_2 = 0. \qquad (1)$$

In the closed circuit indicated by the chain line we have

$$2I_2 + I_1 = 2. \qquad (2)$$

Solving these equations simultaneously we find that $I_1 = 0{\cdot}8$ amp. and that $I_2 = 0{\cdot}6$ amp.

The current in the conductor DC is $-0{\cdot}2$ amp., the negative sign indicating that the current is really flowing against the direction of the arrow.

The total current taken from the cell is $1{\cdot}4$ amp. and the equivalent resistance of the network between the points A and B is $\dfrac{2}{1{\cdot}4} = 1{\cdot}428$ ohm.

CHAPTER IV

RESISTANCE

EXPERIMENT shows that the resistance of any conductor is proportional to its length, and inversely proportional to its area of cross-section; this is expressed by writing

$$\text{Resistance} \propto \frac{\text{length}}{\text{area of section}}$$

or more concisely

$$R \propto \frac{L}{A}$$

This amounts to saying that as long as we are dealing with the same kind of material, doubling the length of a given conductor doubles its resistance, whilst doubling its area of cross-section halves its resistance.

We may further write that

$$R = \frac{L}{A} \times \rho,$$

where ρ is a factor which is constant for any given material (excepting a slight temperature effect discussed later), but which has a different value for different materials.

To find what this number means, notice that if we put length $=1$, and area of section $=1$, we have $R=\rho$, i.e.

ρ is the resistance of a portion of the material of unit length and of unit area of cross-section.

This is called the **Resistivity** (or, more precisely, the **Volume Resistivity**) of the material. It is also sometimes referred to as the specific resistance of the material, and its numerical value will depend upon the units used. If we put R in ohms, length in centimetres, and area in square centimetres, ρ is in "ohms per centimetre cube"; if we use the inch and square

inch it is in "ohms per inch cube," and so on, but as the resistance of such short and thick conductors is usually very low these numbers are small decimals, and hence it is customary to express resistivities in **microhms** (1 microhm = 1 millionth of an ohm, or 1 ohm = 1 million microhms), or in **absolute units** (1 ohm = 1 thousand million absolute units).

Further, the resistivity of very poor conductors may be so enormous that it is conveniently expressed in **megohms** (1 megohm = 1 million ohms).

In order to determine the resistivity of a given material, it is of course not necessary to actually prepare a specimen of unit length and unit section and then measure its resistance; it is sufficient to measure the resistance, length, and cross-section of any convenient portion of the substance, and then apply the formula given above.

Example.—A copper wire 1 metre long and 0·026 cm. in diameter is found to have a resistance of 0·294 ohm. Calculate the specific resistance in microhms per "centimetre cube"

$$\text{Now } R = \frac{L\rho}{A} \quad \therefore \rho = \frac{RA}{L},$$

$$\therefore \quad \rho = \frac{0{\cdot}294 \times 0{\cdot}7854 \times 0{\cdot}026^2}{100} = 0{\cdot}00000156 \text{ ohm per centimetre cube,}$$

$$= 1{\cdot}56 \text{ microhm per centimetre cube.}$$

Table of Resistivities

Material.	Absolute units per centimetre cube.	Microhms per centimetre cube.	Microhms per inch cube.	Ohms per mil-foot.
Copper (pure)	1560	1·56	0·614	9·38
Aluminium	2665	2·665	1·049	16·03
Iron	9065	9·065	3·569	54·53
Platinoid (alloy)	41000	41·0	16·14	246·7
Silver	1468	1·468	0·578	8·83
Mercury	94070	94·07	37·03	565·8
Manganin (alloy)	46000	46·0	18·54	276·8

As regards the last column, the numbers indicate the resistance of a wire 1 mil (1000 mils = 1 inch) in diameter and 1 foot in length. We may note that if *d* is the diameter of a

wire in mils, L its length in feet, and S the resistance (in ohms per mil-foot) of the material of which the wire is composed, then its total resistance will be given by the formula

$$\text{resistance} = \frac{LS}{d^2} \text{ ohms.}$$

It should also be noted that the term centimetre cube or inch cube, is used simply for convenience. It does not matter in the least what the shape of the cross-section is, it may be round or square or wholly irregular, but if its area of section amounts to one square centimetre or one square inch, as the case may be, then the resistance per centimetre or per inch of length will be the same for each shape and is by definition the resistivity.

At the same time the cube is the simplest shape to think of, and the term is sufficiently clear to avoid misconception.

RESISTANCE OF ALLOYS

The table shows that the resistivity of alloys is very much greater than that of ordinary pure metals. This is a very characteristic property of alloys, and is taken advantage of in the preparation of resistance coils for various purposes. Even a slight trace of another metal has an enormous effect relatively to its amount; for instance, experiments carried out at the National Physical Laboratory show that $\frac{1}{10}$ of 1 per cent of aluminium in copper reduces the conductivity (i.e. increases the resistance) of the latter by 23 per cent.

EFFECT OF CHANGE OF TEMPERATURE ON RESISTANCE

Simple experiments will show that the resistance of conductors is altered when the temperature changes; for instance, a yard or so of iron wire, about No. 20 gauge, can be made into a rough helix and connected in series with a suitable ammeter and a cell of fairly low resistance. When the wire is heated by a Bunsen flame, the deflection decreases, returning to practically its old value when the flame is removed; this shows that the resistance of iron increases with rise of temperature.

Again, the resistance of a certain lamp filament made of metallic tantalum was found to be 46·2 ohms when cold and 246 ohms when working; whereas an ordinary carbon

filament was found to have a cold resistance o 360 ohms, which fell to 182 ohms when at work.

Experience shows (1), that the resistance of all pure metals increases with temperature, i.e. they are said to have a "positive" temperature coefficient; (2), the resistance of carbon, and non-metallic conductors (including such liquids and solutions which conduct) decreases as temperature rises, and these are said to have a "negative" temperature coefficient; (3), the resistance of alloys does not vary so much as that of pure metals: a property of great use in the preparation of standards of resistance.

To the electrical engineer this dependence of resistance upon temperature is of enormous importance in the construction of incandescent lamps; it must also be taken into account in designing the windings of dynamos and transformers, for their resistance when heated by a long run may differ considerably from the value measured when cold; it also seriously affects the properties of many insulating materials: glass, slate, etc., become semi-conductors at a temperature below redness, apparently because in all such compound bodies partial electrolytic conduction sets in long before the substance actually fuses. This fact is applied usefully in the Nernst lamp. Again, it means that in all really accurate measurements of resistance the temperature must be carefully taken and specified, and conversely it affords one of the best and most accurate indirect methods of measuring very high and very low temperatures.

For our purpose it is sufficient here to say that there is a remarkable uniformity in the behaviour of nearly all pure metals. If the resistance of wires made from them be measured at the freezing-point of water and then again at the boiling-point, it will be found that each has increased by an amount not far from 40 per cent of its original value: further, the rate of increase is nearly uniform through quite a wide range, though not exactly so.

Iron is an exception and would show an increase of about 60 per cent within these limits; and an especially marked and abnormal increase near a red heat, a property applied usefully in the "ballast" resistance of Nernst lamps.

A very slight admixture of another metal may make a very large alteration in these values, and there is no such

uniformity in the behaviour of alloys; their temperature coefficient may be made very low, it is usually positive, but in some cases may be negative.

The term **temperature coefficient** may be defined as follows :—

$$\textit{Temperature coefficient} = \frac{\textit{Increase in resistance for a rise of } 1^\circ \textit{ C.}}{\textit{Resistance at } 0^\circ},$$

assuming that we are using the centigrade scale.

The definition really assumes that the increase in resistance is uniform per degree, which, as has been already remarked, is nearly true at ordinary temperatures. It also means that we may write—

$$R_t = R_0\,(1 + at).$$

Where R_t and R_0 are the resistances at temperatures t° and 0° respectively, and a is the temperature coefficient.

We may note that the resistance of a coil of wire at 0° C. is seldom known, but the resistance at the temperature of the air can readily be determined, and formulæ can readily be deduced to employ this value rather than the value at 0° C.

If R_1 is the resistance of the coil at a temperature t_1 (the room temperature) and R_2 is the resistance of the coil at some higher temperature t_2, we have

$$\frac{R_2}{R_1} = \frac{R_0(1 + at_2)}{R_0(1 + at_1)} \text{ or } R_2 = R_1\frac{1 + at_2}{1 + at_1}$$

and from this, if it is desired to find t_2, we have by multiplying across, $R_2 + R_2at_1 = R_1 + R_1at_2$

$$\text{whence } t_2 = \frac{R_2 - R_1}{R_1a} + \frac{R_2}{R_1}t_1$$

It should be realised that this formula is based on the assumption that a is constant and it would not be wise to rely on its accuracy for very wide ranges of temperature. The value of a for copper is 0·00428.

When the rise of temperature is moderate, as in the cases of armature and field coils, the second term in the last expression does not differ greatly from t_1, and we have $t_2 = \dfrac{R_2 - R_1}{R_1a} + t_1$ (approximately) and the rise of temperature $= \dfrac{R_2 - R_1}{R_1a}$ (approximately).

This approximation must only be used if the rise of temperature is small and greater accuracy of result may be obtained with it if we take $a=0{\cdot}00393$. This number is really the temperature coefficient in terms of the resistance at an ordinary room temperature (say 20° C. to 25° C.) instead of in terms of the resistance at 0° C.

Example.—A coil of platinum wire is found to have a resistance of 14·2 ohms at a room temperature of 16° C. and a resistance of 17·57 ohms at a temperature of 84° C. Determine the average value of the temperature coefficient between these limits of temperature.

In this case we use the formula $\frac{R_2}{R_1}=\frac{1+at_2}{1+at_1}$

whence $R_2+R_2at_1=R_1+R_1at_2$ and $a=\frac{R_2-R_1}{R_1t_2-R_2t_1}$

$$=\frac{17{\cdot}57-14{\cdot}2}{14{\cdot}2\times 84-17{\cdot}57\times 16}=\frac{3{\cdot}37}{911{\cdot}7}=0{\cdot}0037.$$

Example.—The resistance of a field coil of a dynamo was found to be 70 ohms when cold ; after being in use for some time it was found to have risen to 82·3 ohms. If the temperature of the air was 16° C., calculate the *average* final temperature of the coil.

In this case we may use the approximate formula for temperature rise together with the appropriate coefficient and we have rise in temperature

$$=\frac{R_2-R_1}{R_1a}=\frac{82{\cdot}3-70}{70\times 0{\cdot}00393}=\frac{12{\cdot}3}{0{\cdot}2751}=44{\cdot}7^\circ \text{ C.}$$

and the actual average temperature of the coil is

$$44{\cdot}7+16=60{\cdot}7^\circ \text{ C.}$$

Note, the surface temperature of the coil, as measured with a thermometer, will have a lower value than is indicated by this figure while the central parts will be hotter.

EQUIVALENT RESISTANCE OF CONDUCTORS IN PARALLEL

Let any number of conductors whose resistances are R_1, R_2, R_3, etc., be joined up in parallel as shown in Figure 49 to points A and B in a circuit, and let the total current be

I amperes, which divides between them into portions I_1, I_2, I_3, etc.

Let R be the equivalent resistance, that is, the single resistance which might be substituted for all the parallel conductors without altering the resistance between A and B.

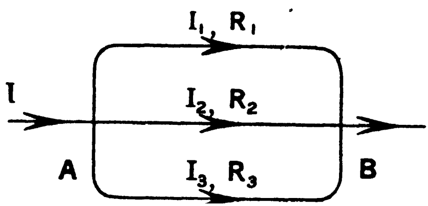


FIG. 49.

Notice that a suitable voltmeter connected between A and B would measure a certain P.D. which is the same for all the conductors; let this be V volts, then by the definition of R,

$$I=\frac{V}{R},$$

$$\text{and } I=I_1+I_2+I_3+\text{etc.},$$

$$\text{also by Ohm's Law } I_1=\frac{V}{R_1},$$

$$I_2=\frac{V}{R_2},$$

$$I_3=\frac{V}{R_3}, \text{ etc.},$$

$$\therefore\ I_1+I_2+I_3+\text{etc.}=\frac{V}{R_1}+\frac{V}{R_2}+\frac{V}{R_3}+\text{etc.},$$

$$\text{or } \frac{V}{R}=\frac{V}{R_1}+\frac{V}{R_2}+\frac{V}{R_3}+\text{etc.},$$

$$\therefore\ \frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\text{etc.},$$

$$\text{and } R=\frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\text{etc.}}$$

Example.—Resistances of 3, 4, and 5 ohms are connected in parallel. Calculate the equivalent resistance.

$$\text{From above } R=\frac{1}{\frac{1}{3}+\frac{1}{4}+\frac{1}{5}}=\frac{60}{47}=1\cdot28 \text{ ohm.}$$

It will be noticed that when the resistances in parallel are all equal, the equivalent resistance is obtained by dividing the resistance of one of them by the total number in parallel: for suppose there are 6 resistances each of 3 ohms, then

$$R=\frac{1}{\frac{1}{3}+\frac{1}{3}+\frac{1}{3}+\frac{1}{3}+\frac{1}{3}+\frac{1}{3}}=\frac{1}{\frac{6}{3}}=0\cdot5 \text{ ohm.}$$

This result of course applies to the case of a number of lamps in parallel, which has already received attention.

It will be noticed that the equivalent resistance is always less than the *least* of the individual resistances; for instance, if 1000 ohms is joined up in parallel with 1 ohm, the equivalent resistance is under 1 ohm.

Example.—If 75 yards of $\frac{7}{16}$ cable are in parallel with 50 yards of $\frac{19}{20}$ cable, what is the joint resistance? Assume that a single 16-gauge wire has a resistance of 0·8 ohm per 100 yards, and a single 20-gauge wire has a resistance of 2·75 ohms per 100 yards, and that the resistance of a stranded conductor may be taken as 3 per cent greater than that of a straight conductor of equal section (C and G).

In the case of the $\frac{7}{16}$ cable we know that 100 yards of a single 16 has a resistance of 0·8 ohm,

$$\therefore \text{ 75 yards has a resistance of } \frac{75}{100}\times 0\cdot8=0\cdot6 \text{ ohm.}$$

Since there are 7 strands in parallel, the resistance of 75 yards will be $\frac{0\cdot6}{7}$ ohm.

This assumes that each of the seven wires is exactly 75 yards in length; really it is the made-up cable which has this length, and as the strands are twisted the actual length of each will be more than 75 yards (except in the case of the centre one): an extra 3 per cent is to be allowed for this;

$$\therefore \text{ actual resistance of 75 yards of } \tfrac{7}{16} \text{ cable}=\frac{0\cdot6}{7}+\left(\frac{3}{100}\times\frac{0\cdot6}{7}\right)$$
$$=0\cdot088 \text{ ohm.}$$

Similarly we have

100 yards of single 19 has a resistance of 2·75 ohms,

$\therefore$ 50 ,, ,, ,, ,, 1·375 ,,

and resistance of 19 strands in parallel $=\frac{1 \cdot 375}{19}$,

and resistance of 50 yards of cable $=\frac{1 \cdot 375}{19} \times \frac{103}{100}=0 \cdot 074$ ohm.

We have, then, two resistances of 0·088 ohm and 0·074 ohm in parallel,

$$\text{Now } R=\frac{1}{\frac{1}{R_1}+\frac{1}{R_2}}=\frac{1}{\frac{R_1+R_2}{R_1R_2}}=\frac{R_1R_2}{R_1+R_2}$$

$$=\frac{0 \cdot 088 \times 0 \cdot 074}{0 \cdot 088+0 \cdot 074}=0 \cdot 040 \text{ ohm.}$$

Example.—Three lengths of cable having resistances of 0·035, 0·025, and 0·013 ohm respectively, are joined in parallel and used to carry a current of 80 amperes.

How much of this current flows through each of the three cables, and what is the P.D. between the two ends of the combination ?

Let R be the equivalent resistance, then

$$R=\frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}}=\frac{1}{\frac{1}{0 \cdot 035}+\frac{1}{0 \cdot 025}+\frac{1}{0 \cdot 013}}=0 \cdot 0069 \text{ ohm.}$$

If V = P.D. across combination, then

$$V=IR=80 \times 0 \cdot 0069=0 \cdot 55 \text{ volt.}$$

and current 0·035 ohm resistance $=\frac{V}{R_1}=\frac{0 \cdot 55}{0 \cdot 035}=15 \cdot 7$ amperes.

" " 0·025 " " $=\frac{V}{R_2}=\frac{0 \cdot 55}{0 \cdot 025}=22 \cdot 0$ "

" " 0·013 " " $=\frac{V}{R_3}=\frac{0 \cdot 55}{0 \cdot 013}=42 \cdot 3$ "

CHAPTER V

POWER AND ENERGY IN RELATION TO ELECTRICAL CIRCUITS

USEFUL ideas concerning power in electrical circuits can be obtained by a further consideration of the example used to illustrate Ohm's Law on page 47.

In this example, in case (*a*), the lamps as a whole took 0·55 ampere at a voltage of 50,000, while in case (*b*) they took 275 amperes at a voltage of 100. The individual lamps gave out light at the same rate and had equal inputs in both cases, so that it is reasonable to suppose that the total power put into the lamps was also equal in the two cases. We see, however, that the total currents and the total voltages differ enormously in the two cases and we conclude that we can get no idea of the power involved from a consideration of either the current or voltage alone.

If, however, we multiply current and voltage we obtain the same result in each case for

$$\text{in } (a)\ V \times I = 50{,}000 \times 0{\cdot}55 = 27{,}500,$$
$$\text{and in } (b)\ V \times I = 100 \times 275 = 27{,}500.$$

What does this number mean ? Obviously it does not afford a basis on which we can pay for the light, because it does not take into account how long it may be used, and therefore it does not indicate the total work done, and is not in units of work.

On the other hand, it does indicate how much work is being done per second, or per minute, or in any given time whilst the lamps are alight, and is therefore a measure of the *rate of working*, that is, of the *power* expended in the lamps.

Here a brief digression may be of use, and absolute clearness of ideas on these points must be aimed at.

In the first place, when we speak of the cost of light, we must remember that the only definite and tangible quantity we can measure and pay for is "work" in the scientific sense of the term. "Energy" is an almost convertible term, and the two words may be at first taken to mean the same thing, the latter usually referring to the amount of work it is possible to do, whether actually done or not. That is, the energy of a body is the amount of work it can do.

Forces of any magnitude may act on a body, but work is only done when displacement occurs, and then it is measured by the product of force and displacement. Two units of work will be chiefly used in this book: (1) the foot pound, (2) the Board of Trade Unit or Kilowatt-hour.

The **foot pound** is the amount of work done when a force equal to the weight of one pound acts through a distance of one foot.

The simplest case is that of a pound weight lifted one foot vertically, but it must be remembered that this is not the definition; a force equal to one pound weight may be overcome through a distance of one foot in any direction whatever.

The foot pound is not a strictly scientific unit; it is simply a convenient one, the point here being that one foot pound, or any number of foot pounds, is something completely defined, which can be paid for without reference to anything else.

It should be especially noted that work is always the product of two quantities; the mere exertion of a force will not do work.

The cost or value of a foot pound of work does not depend in the least upon the time in which it is done, whereas the value of "power," or "rate of working," depends upon the time for which this rate of working is continued; we may say in fact that

$$\text{Work} = \text{Power} \times \text{Time during which it is exerted.}$$

For instance, anyone can do 33,000 foot pounds of work if he is given an unlimited time in which to do it, but if the task is to be accomplished in one minute, the agent must work at the rate of 33,000 foot pounds per minute, or, as it is called, 1 Horse-power.

If the 33,000 foot pounds of work is to be done in half a minute, the agent must work at the rate of 66,000 foot pounds

per minute, that is, 2 Horse-power, but the final result and the money earned is equal in both cases.

Hence power is not a definite and tangible thing which can be bought and sold as such : its scientific meaning is the rate of doing work, that is, the amount of work performed in unit time, and it is correctly used in the common term Horse-power, defined as above as being equivalent to a rate of working of 33,000 foot pounds per minute or, what amounts to the same thing, 550 foot pounds per second.

Power cannot be paid for until we know how long it has been in use, then we can reckon up the total work done.

For instance, we cannot state the value of 10 Horse-power (H.P.), whereas the value of 10 H.P. for one hour, or one year, can be at once reckoned up in terms of work.

To explain the term " Board of Trade Unit " we now return to the question of lamps.

It will appear from what has been said that the energy expended in them depends only upon the current, the voltage, and the time for which they are run.

The current and voltage multipled together gives the power used in terms of a unit called the **watt**, which is the *rate of working corresponding to one ampere flowing through a circuit, the P.D. between whose terminals is one volt.*

The watt is therefore a similar unit to the Horse-power, and it can be shown that 1 H.P. $=746$ watts.

Hence it follows that one watt is a rate of working of

$$\frac{33000}{746}=44\tfrac{1}{4} \text{ (nearly) foot pounds per minute.}$$

In the example already given the power VI came to 27,500 watts, hence the H.P. supplied to the lamps will be

$$\frac{27500}{746}=36{\cdot}8 \text{ H.P.}$$

Let the lamps run for 24 hours, then the work done will be $36{\cdot}8\times 33{,}000$ foot pounds per minute, and as there are 24×60 minutes in 24 hours, the total work done will be

$$36{\cdot}8\times 33000\times 24\times 60=1{,}749{,}000{,}000 \text{ foot pounds (nearly).}$$
$$=1{\cdot}749\times 10^9 \text{ foot pounds.}$$

This can be paid for at some fixed rate per foot pound, but it is not convenient to express work in foot pounds, chiefly

on account of the smallness of the magnitude of this unit; the unit employed in practice is the **kilowatt-hour** (kWh), or the *amount of work done by a power of one kilowatt* (*or* 1000 *watts*) *acting for one hour.*

Evidently it is the work done in one hour by $\frac{1000}{746}=1\frac{1}{3}$ H.P., and is equal to

$$\frac{1000}{746}\times 33000\times 60=2{,}654{,}000 \text{ foot pounds.}$$

This quantity of work is called a "Board of Trade" unit (B.O.T. unit) and is also sometimes termed a "Kelvin."

To find the cost of running lamps taking 27,500 watts for 24 hours we will assume the cost of a B.O.T. unit to be fourpence (a very usual price for lighting purposes).

$$\begin{aligned}\text{Work done} &= 27500\times 24 \text{ watt hours,}\\ &= \frac{27500\times 24}{1000} \text{ kilowatt-hours,}\\ &= 660 \text{ B.O.T. units.}\\ \text{Cost of work} &= 660\times 4 \text{ pence}\\ &= \frac{660\times 4}{12} = 220 \text{ shillings}\\ &\text{or } £11.\end{aligned}$$

Another unit of work occasionally used in electrical matters is known as the **joule**; it is the *amount of work performed by one watt acting for one second.* It is of little importance in practical work on account of its small magnitude, and in any case it is more intelligible to speak of it as a **watt-second.**

So far, when calculating power, we have used the product of current and voltage or $P=VI$, but if the resistance of the circuit (real or equivalent) is denoted by R we have, from Ohm's Law, $V=IR$ and $I=\frac{V}{R}$. Substituting these in turn in the above expression for power we have the alternative expressions $P=I^2R$ and $P=\frac{V^2}{R}$ respectively. The result in each case being in watts if current, voltage, and resistance are measured in amperes, volts, and ohms respectively. If we

desire the power to be expressed in kilowatts the expressions become $P = \frac{VI}{1000} = \frac{I^2R}{1000} = \frac{V^2}{1000\,R}$.

Finally, any of the last set of expressions, when multiplied by the time in hours during which the circuit is in use, will give the energy consumed in kilowatt-hours or Board of Trade Units.

LOSS OF ENERGY IN RESISTANCE

When there is only one E.M.F. acting in a circuit, all the electrical energy given to that circuit is dissipated as heat. This is the only case so far considered, and the loss due to the resistance of the circuit can be calculated by using any one of the expressions for power which are given above.

These three expressions have the same numerical value and we may use whichever is most convenient, but for the particular purpose of estimating the heat loss in a conductor the form I^2R is the safest to use, because in all circumstances and in all conditions, and no matter how many E.M.Fs. there are in the circuit, or whether current be continuous or alternating, if a current of I amperes flow through a resistance of R ohms this loss is I^2R watts.

The other forms are equally correct if we understand V to represent the voltage actually acting upon the resistance considered, but to a beginner there is more risk of error.

When calculating the power losses in field and armature coils the resistance of the coil at the working temperature should always be used. This is likely to be some 16 per cent higher than the resistance at the room temperature and will cause a corresponding change in the loss.

EFFECT OF COUNTER-VOLTAGES IN CIRCUITS

In the examples hitherto considered there has only been one voltage in the circuit (i.e. the voltage sending the current), and in such cases the whole of the input is converted into heat, but in some circuits, due to the presence of an accumulator on charge or to a motor, there is a counter E.M.F. (of course of less magnitude than the applied voltage). In such cases the power supplied to the circuit is not all converted into heat, a portion being usefully used in other ways. For

example, in the case of a motor, a portion of the input is converted into mechanical power.

For instance, let BC (Figure 50) represent a portion of a circuit carrying a current of 4 amperes, the P.D. between B and C being 24 volts.

Then we can safely say that the power expended in BC is VI watts$=24\times4=96$ watts, but unless we know something

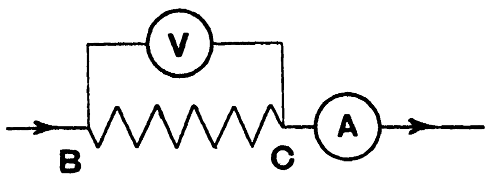


FIG. 50.

about the nature of BC, we cannot say how it is expended. If BC is merely a wire or any other resistance, then that resistance is evidently 6 ohms, and the 96 watts will be converted into heat.

If we use the form I^2R, we get $4\times4\times6=96$ watts, and similarly the form $\frac{V^2}{R}$ gives $\frac{24\times24}{6}=96$ watts.

If between B and C there is a motor, or accumulators which are being charged, then we can still safely say that the power expended is 96 watts, but it would be wrong to infer that the resistance is 6 ohms. It will certainly be less than that, and its value cannot be found from the readings of the instruments. If we know by other means that its value is 2 ohms, then it follows that the power expended as heat in BC is $I^2R=4\times4\times2=32$ watts, and the balance represents power converted into some other form of work.

Notice further that only 8 volts are required to send 4 amperes through 2 ohms; therefore in this case there must be a "back E.M.F." of 16 volts; if we denote this by E_b, the equation of current becomes—

$$I=\frac{V-E_b}{R}=\frac{24-16}{2}=4 \text{ amperes.}$$

Remember that the back E.M.F. itself can never be read

on the instruments, but when it exists we have the following simple relations :—

Impressed E.M.F. $\times$ Current = power supplied.
Back E.M.F. $\times$ Current = power converted into some kind of work.
Difference = power wasted as heat in conductors = I^2R loss.

Now consider a simple lighting circuit, consisting of a "generator" of some kind, connected by conducting wires (called the "mains" or "leads") to a number of lamps some distance away.

In this case all the energy supplied is converted into heat, but efficiency demands that as much of the heat as possible shall be produced in the lamps, and as little as possible in the generator and leads. In Figure 51 A and B are the terminals

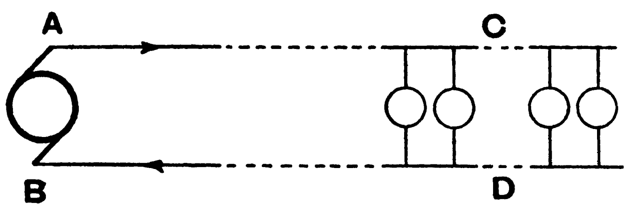


FIG. 51.

of the generator, the lamps are clustered across CD, and AC and BD represent the two leads. Suppose that there are 154 lamps to be supplied, each consuming 60 watts at a voltage of 110. This statement means that the voltage across CD must be 110 in order that each lamp may have its due working current; it also means that the current taken by any one lamp is such that $V \times I = 60$ watts,

$$\therefore \; I = \frac{60}{V} = \frac{60}{110} = 0 \cdot 545 \text{ ampere,}$$

$\therefore$ the total current will be $0 \cdot 545 \times 154 = 84$ amperes, and the power taken by the lamps will be

$$110 \times 84 = 9240 \text{ watts.}$$

This power has to be transmitted from generator to lamps by means of the leads, and as some loss of energy due to heat produced in them is inevitable, the power given out by the generator must be greater than 9240 watts. How much greater is a matter entirely at our own disposal, for by using sufficiently thick conductors the loss can be made as small as we please, but on the other hand the cost of such thick conductors soon becomes prohibitive. Without going further into this question at present, we will assume the permissible loss is 5 per cent of the power delivered; this comes to be

$\frac{5}{100} \times 9240 = 462$ watts.

Hence $9240 + 462 = 9702$ watts must be supplied by the generator at AB, but it must be clearly kept in view that this does not mean the current is stronger at AB, and gradually falls to 84 amperes at CD.

The current is of necessity exactly the same strength all round the circuit, whether inside the generator, in the leads, or in the lamps (the sum of the currents passing through the several lamps must here be considered).

It follows then that the P.D. across AB is greater than the P.D. across CD, its value being given by

$$V_{AB} \times 84 = 9702$$

$$\text{or } V_{AB} = \frac{9702}{84} = 115{\cdot}5 \text{ volts.}$$

It is worth while examining this instance in detail; it illustrates the meaning of the term "drop," which in this case is 5·5 volts. This means that the resistance of the leads is such that 5·5 volts are required to send 84 amperes through them alone. If R be the total resistance of both leads (that is, twice the resistance of one lead), and if V is the "drop"

$$V = IR$$

$$5{\cdot}5 = 84R,$$

$$\therefore\ R = \frac{5{\cdot}5}{84} = 0{\cdot}065 \text{ ohm.}$$

The resistance from A to C or from B to D is half this.

A voltmeter connected between A and B would read 115·5 volts, between A and C or B and D 2·75 volts, and across CD it would read 110 volts.

We may further note in passing, though it is not of importance as far as this example is concerned, that this 115·5 volts does not represent the total E.M.F. generated. The generator will have a certain internal resistance and a certain E.M.F. will be necessary to drive the current through this resistance, with the result that the P.D. at the terminals of the machine will always be less than the E.M.F. generated.

If the internal resistance of the generator is constant, this internal "drop" will be proportional to the current taken from the generator, and this partly explains why if the E.M.F. generated is constant, the P.D. at the terminals falls off as the current taken is increased (see p. 148).

Resuming our discussion of the example given above, it will be evident that we may also calculate the resistance of the mains by saying that I^2R watts are to be wasted in them.

$$\therefore \; I^2R = 462 \text{ or } R = \frac{462}{I^2} = \frac{462}{84^2} = 0{\cdot}065 \text{ ohm.}$$

Having obtained the resistance we can find the area of section to give that resistance from our knowledge of the resistivity of the material and the length of the leads. Let us assume that the distance between the generator and the lamps is half a mile and take the resistivity of copper to be 0·66 microhm per cubic inch.

$$\text{Now } R = \frac{\text{length in inches}}{\text{Area in square inches}} \times \frac{0{\cdot}66}{10^6}$$

$$\therefore \text{ Area in square inches} = \frac{\text{length in inches} \times 0{\cdot}66}{R \times 10^6}$$

$$= \frac{0{\cdot}5 \times 2 \times 1760 \times 36 \times 0{\cdot}66}{0{\cdot}065 \times 10^6} = 0{\cdot}64 \text{ sq. in.}$$

The following representative examples have been chosen to illustrate the methods of calculation used in connection with problems of power and work in electrical circuits and also in connection with problems involving conversions of energy. Their solution requires not only a knowledge of the matter already dealt with in this chapter but also, except in the first one, some knowledge of the matter dealt with in the appendix to the chapter.

Example.—It is required to transmit 60 kW, the voltage at the receiving end being 440. If the cable used has a resistance of 0·14 ohm per mile, what is the greatest distance of transmission if the loss in the cable is not to exceed 10 per cent of the power transmitted ?

$$\text{Current} = \frac{60000}{440} = 136{\cdot}4 \text{ amperes.}$$

$$\text{Loss in cables} = \frac{10}{100} \times 60 \times 1000 = 6000 \text{ watts.}$$

Now loss in cable $= I^2R$ $\therefore$ resistance of cable

$$= \frac{6000}{136{\cdot}4^2} = 0{\cdot}3227 \text{ ohm.}$$

$$\text{Distance of transmission} = \frac{0{\cdot}3227}{{\cdot}14 \times 2} = 1{\cdot}152 \text{ mile.}$$

Example.—A water turbine driving a dynamo receives 200,000 gallons of water per hour at an effective head of 120 feet. If the efficiency of the turbine and dynamo is 70 per cent and 90 per cent respectively, calculate the input and output of the turbine and dynamo. What current can be taken from the dynamo if the P.D. at the terminals is 220 volts ? Since one gallon of water weighs 10 pounds, the input to the turbine $= \dfrac{200000 \times 10 \times 120}{60}$

$= 4{,}000{,}000$ foot-pounds per minute

$$= \frac{4000000}{33000} = 121{\cdot}2 \text{ H.P.}$$

$$\text{Output of turbine} = \frac{121{\cdot}2 \times 70}{100} = 84{\cdot}84 \text{ H.P.}$$

This will also be the input to the dynamo if the losses in the coupling are negligible.

$$\text{Output of dynamo} = \frac{84{\cdot}84 \times 90 \times 0{\cdot}746}{100} = 56{\cdot}95 \text{ kW.}$$

Current obtainable from the dynamo $= \dfrac{56{\cdot}95 \times 1000}{220} = 258{\cdot}9$ amps.

Example.—A tramcar weighing 10 tons requires a total tractive force of 350 pounds to move it at a speed of 12 miles per hour. If the efficiency of motors and gearing is 60 per cent and the supply voltage is 500, calculate the current taken from the line. What will be the charge for energy per car-mile if the price is 0·75 penny per B.O.T. unit ?

Now 12 miles per hour $=\frac{12 \times 5280}{60}=1056$ feet per minute, and the H.P. actually required for tractive purposes will be

$$\frac{1056 \times 350}{33000}=11 \cdot 2.$$

Power from line $=\frac{11 \cdot 2 \times 100 \times 0 \cdot 746}{60}=13 \cdot 92$ kW.

Current from line $=\frac{13 \cdot 92 \times 1000}{500}=27 \cdot 84$ amperes.

The time taken to travel one mile will be $\frac{1}{12}$ hour, therefore the cost of energy per car-mile will be $\frac{13 \cdot 92 \times 0 \cdot 75}{12}=0 \cdot 87$ penny.

Note, that the calculations given above correspond to steady running and do not, without suitable modification, apply to periods of varying speed.

Example.—What time will be taken to raise the temperature of 4 pints of water from 62° F. to the boiling point if the kettle takes 6 amperes at 230 volts and has an efficiency of 90 per cent ?

The rise of temperature is $212-62=150°$ F., and the energy required by the water will be $\frac{4 \times 10 \times 150}{8}=750$ B.Th.U.

The energy input to the kettle will be $\frac{750 \times 1058 \times 10}{9}$ joules.

Now power × time = work (or energy),

$$\therefore \text{ time} = \frac{\text{work}}{\text{power}} = \frac{750 \times 1058 \times 10}{230 \times 6 \times 9} = 639 \text{ seconds.}$$

If energy is charged at the rate of twopence per B.O.T. unit the cost will be $\frac{6 \times 230 \times 639 \times 2}{1000 \times 3600}=0 \cdot 49$ penny.

APPENDIX TO CHAPTER V

NOTES ON UNITS

In electrical measurements we have to distinguish between (1) **absolute units,** (2) **practical units,** and (3) **standards of reference** in which these units are realised. The absolute units are obtained first in discussing the theory of the subject. In their case convenience in size and in direct application is unimportant, the chief points being rigidity of definition and logical connection with other units. When necessary, one or more multiples or sub-multiples of an absolute unit are chosen to serve as practical units, and for convenience in making measurements actual standards embodying these units are constructed when it is possible to do so.

The following is a short summary which shows the relationship of the principal electro-magnetic units to each other. These units are so interconnected that it is possible to define most of them in several alternative ways. We have not always followed a strictly ideal sequence, preferring simple definitions suitable for beginners. A full treatment of the subject would be out of place in this book. Also we assume that the reader is already acquainted with the C.G.S. units of force and work, the **dyne** and the **erg.**

Unit Magnetic Pole.—This is an ideal magnetic pole of such strength that when placed in a vacuum at a distance of 1 centimetre from another equal pole ((both being *points*) the force of attraction or repulsion between them is 1 dyne. It should be noted that unless the poles are really ideal points in size the definition fails. We cannot accurately realise such a pole in practice, (1) because we cannot isolate a *single* pole, (2) because real poles are not points ; but, on the other hand, there is no necessity to realise it practically. It is shown later that this is really a unit of magnetic field.

Unit Magnetic Force is said to exist at a point in a magnetic field at which **Unit Pole** is acted upon by a force of 1 dyne. Its value may be expressed as so many dynes per unit pole.

A closely allied expression is **Magnetising Force** which is used in connection with a flux set up by a current in a magnetising coil. It is defined as Magneto-motive Force (see page 178) per cm. measured along a line of magnetic flux. It is expressed as so many gilberts per cm., and denoted by the symbol H. In the case of a magnetic circuit in vacuo along which the magnetising

force is uniform, it will be realised that the magnetic force in dynes per unit pole will be numerically equal to the magnetising force in gilberts per cm.

Unit Magnetic Flux Density (B) is produced in vacuo where the magnetising force is one gilbert per cm.; it is represented by one line of magnetic flux (or maxwell) per sq. cm. taken at right angles to the direction of the lines. It is sometimes referred to as a magnetic flux density of one gauss, but it would appear to be wiser for engineers to employ the term one line per sq. cm. In iron the same value of magnetising force would produce a much more intense flux density whose value may be obtained by multiplying the magnetising force by the permeability (μ) of the iron. The relation between H and B is embodied in the equation $B = \mu H$, in which $\mu = 1$ for vacuo and practically 1 for air and other so-called non-magnetic bodies.

Number of Lines from Unit Pole.—In the light of the last three definitions, we may regard the force acting on either of the unit poles in the first definition as the result of its presence in the field due to the other pole. This implies that at a distance of 1 centimetre from a unit pole in air there exists a magnetic flux density of unit strength (i.e. 1 line per square centimetre). If we describe a sphere of radius 1 centimetre, with the pole as its centre, its surface will be penetrated by 1 line per sq. cm., and as its actual surface is 4π sq. cms., it follows that our method of defining unit pole and unit magnetic flux density incidentally determines that a unit pole possesses 4π lines of magnetic flux. It is evident, therefore, that a unit pole is really a particular kind of unit of magnetic field, representing 4π lines of magnetic flux diverging from a mathematical point.

Unit Current.—The fact that a magnetic field exists in the space around a current may be employed as follows in defining the unit. A current is said to have a strength of one absolute unit if, when flowing in a conductor 1 centimetre long bent to form the arc of a circle 1 centimetre in radius, it exerts a force of 1 dyne upon a unit magnetic pole placed at the centre of the circle. (Conversely, the unit pole exerts a force of 1 dyne upon the conductor.)

In this form the definition is incapable of direct application, but more convenient expressions are readily obtainable, as in the well-known case of the tangent galvanometer.

The practical unit of current is known as the **Ampere,** and its value depends on the way we define the units of E.M.F. and resistance. It will be seen later that the ampere is $\frac{1}{10}$ of the absolute unit as defined above. The ampere is also defined as being the current which liberates ·001118 grams of silver per

second in electrolysis. This definition lends itself readily to exact measurement.

Unit Quantity.—This is the quantity of charge corresponding to 1 absolute unit of current flowing for 1 second, or $Q = It$, where I is the current in absolute units and t is the time in seconds. The practical unit corresponds to 1 ampere flowing for 1 second and is known as a **Coulomb.** It may also be called an **Ampere-second.** As the ampere is $\frac{1}{10}$ of an absolute unit of current, it follows that the coulomb is $\frac{1}{10}$ of the absolute unit of quantity. A larger unit of quantity, the **Ampere-hour,** is often used, especially in rating accumulators. It is evidently equal to 3600 coulombs.

Electromotive Force or Potential Difference.—This may be defined in several ways. For instance, on page 87 the absolute unit of E.M.F. is defined as being the induced E.M.F. produced when a conductor cuts 1 line of magnetic flux per second. It may also be defined as the P.D. which must exist between two points in a circuit, when 1 erg of work is done on, or done by, 1 absolute unit of quantity in flowing from one point to the other. Here a P.D. may be regarded as the analogue of a height, and a quantity of electricity as a mass. Work must be done in moving the mass through the height, and it is done on or by the mass, accordingly as the motion is set up or down.

The absolute unit of E.M.F. is too small for most purposes, and the practical unit, the **Volt,** is 10^8 absolute units. The choice of the multiplier was originally a matter of convenience, and the number 10^8 was selected because it made the volt very nearly equal to the E.M.F. of a Daniell's cell, which at the time was used extensively for telegraphic purposes. Standards of E.M.F. of a very convenient kind can be readily made in the form of cells, the Cadmium cell, whose E.M.F. is about 1·02 volts, being most generally used.

Resistance.—In defining the units of E.M.F. and current we have incidentally defined the unit of resistance, which follows from Ohm's Law. Hence we may say that a conductor possesses 1 absolute unit of resistance when a P.D. of 1 absolute unit of E.M.F. maintains in it 1 absolute unit of current. This unit is also very small, and the practical unit, the **Ohm,** is 10^9 absolute units. This multiplier is again quite arbitrary, and the reason for its selection would not be wholly intelligible without going further into the subject, but it would have been better to have selected 10^8, as in the case of the volt, because then the practical and absolute units of current would have been identical in value. As it is, these multipliers make the ampere $\frac{1}{10}$ of the absolute unit of current, as already stated. Standards of resistance are

easily constructed and compared. For instance, the ohm may be defined as being the resistance of a mercury column of uniform bore, 106·3 centimetres in length and 1 square millimetre in cross-section at a temperature of 0° C. It may be pointed out that in constructing an actual standard of this kind we should not attempt to find a tube of exactly the required section, which would be an impossible task. It is sufficient to determine the actual dimensions in order to calculate its resistance in terms of the above definition.

Work.—The absolute unit of work is the **Erg.** It has been stated that when 1 absolute unit of quantity flows through a P.D. of 1 absolute unit the work done is 1 erg. Hence when a quantity Q flows through a P.D. of value V units the work done is QV ergs. But $Q = It$; $\therefore$ Work $= IVt$ ergs. To find the work done when 1 ampere flows for 1 second through a P.D. of 1 volt, we must express these quantities in absolute units, or Work $= 10^8 \times \frac{1}{10} \times 1 = 10^7$ ergs $= 1$ Joule. The practical unit of work is therefore 10^7 ergs and is termed a "Joule." Consequently we may write Work $= VIt$ Joules $= VIt \times 10^7$ ergs, when V and I are expressed in volts and amperes respectively.

It has already been shown that $VI = I^2R = \frac{V^2}{R}$, and therefore we can express electrical work in any of the forms VIt, I^2Rt, $\frac{V^2t}{R}$.

Power.—Power is measured by the rate at which work is done, and the absolute unit will be a rate of 1 erg per second. The practical unit is 1 Joule per second and is termed a **Watt.**

Hence 1 watt $= 10^7$ ergs per second.

Also Power $= \frac{\text{Work}}{\text{time}} = \frac{VIt}{t} = VI$ watts, where $VI = I^2R = \frac{V^2}{R}$. For many purposes the watt is too small and the **Kilowatt** (1000 watts) is commonly used.

Work (*continued*).—Evidently the Joule, already defined, may be termed a **Watt-second.** Similarly the much larger unit used in practice is termed a **Kilowatt-hour** (kWh.). Alternative names are **Board of Trade Unit** (B.O.T. unit) and the **Kelvin.**

Evidently 1 kWh. $= 1000 \times 3600$ Joules or watt-seconds.

Relationship between Mechanical and Electrical Units of Power and Work.—The relationship between the Joule and the foot-pound is often required. As 1 foot $= 30{\cdot}48$ cms., and 1 lb. weight $= 453{\cdot}6 \times 981$ dynes, we have

$$1 \text{ ft.-lb.} = 30{\cdot}48 \times 453{\cdot}6 \times 981 = 1{\cdot}356 \times 10^7 \text{ ergs.}$$

$$\text{Now } 1 \text{ Joule} = 10^7 \text{ ergs.}$$

$$\therefore 1 \text{ foot-pound} = 1{\cdot}356 \text{ Joules.}$$

Horse-power.—The horse-power is defined as a rate of working of 33,000 ft.-lbs. per minute, or 550 ft.-lbs. per second.

$\therefore$ from above, 1 H.P. $=550\times 1{\cdot}356$ Joules per second.

But 1 Joule per second $=1$ watt.

$$\therefore\ 1\text{ H.P.}=550\times 1{\cdot}356=746\text{ watts.}$$

And 1 H.P. $=\cdot 746$ kilowatt (practically $\frac{3}{4}$ kilowatt),

1 kW. $=1{\cdot}34$ H.P. (practically $1\frac{1}{3}$ H.P.).

Relationship between Heat Units and Electrical Units of Work.—Two heat units are of practical importance. (1) The **Calorie,** defined as being the quantity of heat required to raise the temperature of 1 gram of water through 1° C. (2) The **British Thermal Unit** (B.Th.U.), which is the quantity of heat required to raise the temperature of 1 lb. of water through 1° Fahr. As 1 lb. is equivalent to 453·6 grams, and 1° F. is $\frac{5}{9}$ of a centigrade degree, it follows that 1 B.Th.U. $=252$ calories. The relationship between the units of heat and work cannot be found from first principles, but must be determined experimentally. The result is

$$1\text{ Calorie}=4{\cdot}18\text{ Joules}=4{\cdot}18\times 10^7\text{ ergs.}$$

$$\therefore\ 1\text{ B.Th.U.}=4{\cdot}18\times 252=1058\text{ Joules}=1058\times 10^7\text{ ergs.}$$

CHAPTER VI

MECHANICAL ACTIONS BETWEEN MAGNETIC FIELDS. ELECTRO-MAGNETIC INDUCTION

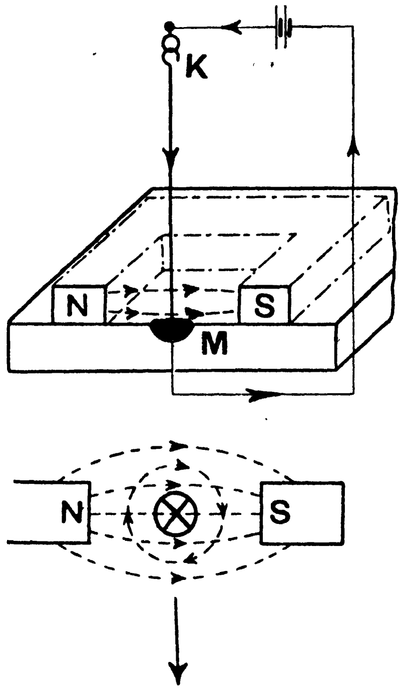
TWO distinct experimental facts form the basis on which is founded the commercial generation of electrical energy and its utilisation as motive power. To emphasise their far-reaching importance we will, for convenience, give them names, and term them the "generator" and "motor" principles respectively.

THE MOTOR PRINCIPLE

The latter or motor principle may be experimentally illustrated as follows (see Figure 52): A piece of copper wire K is loosely hooked through a copper ring at the top, while the lower end dips into a pool of mercury M contained in a hollow formed in a wooden block; a battery of a few cells is connected to the wire and the mercury as shown, thus enabling us to pass a current through the wire and yet allow it some freedom of motion. No effect is produced by the passage of the current alone, but if in addition a magnetic field be provided at right angles to the wire, as by placing a horse-shoe magnet (either a permanent or electro-magnet will do) in the position indicated, a mechanical force at once becomes evident, the suspended conductor being driven at right angles to the plane of the paper in one direction or the other until it breaks contact with the mercury. This interrupts the current, the force disappears, the conductor swings back, and the cycle of movements is repeated. Thus the wire is kept in motion, not swinging symmetrically like a pendulum, but in a series of half swings, receiving an impulse in the same direction whenever it makes contact with the mercury.

We also find that the direction of motion is reversed by either reversing the direction of the current or the polarity of the magnet, but is unaltered if we reverse both.

The effect therefore depends upon the field and current conjointly, and further, it is essential that the current should flow in a direction inclined to the lines of magnetic flux. It is not easy to verify this accurately in a simple way, and so it will for our purpose be sufficient to state that there is no mechanical force, no matter how strong the current or how strong the field, if the current be parallel to the lines of magnetic flux, and that there is some force in all other positions, the force reaching a maximum (for a given current and strength of field) when the current is at right angles to the direction of the field.



Direction of force.

FIG. 52.

The magnitude of this force depends only upon the strength of current, the strength of field, and the length of conductor actually effective, and on this force all practical motors depend for their action.

We can therefore state the motor principle as follows :—

If a conductor carry a current at an angle to the lines of magnetic flux in a uniform magnetic field (the effect is greatest when the angle is a right angle), there is a mechanical force exerted on it tending to move it in a path parallel to itself at right angles to both the directions of field and of current.

This force is independent of the material of the conductor, and its value per unit length of conductor only depends upon

the strength of the current, the strength of the field, and the angle between their directions.

It would, however, be fatal to our future progress to leave the matter in this way; we can easily look a little deeper into the question, but for this purpose the knack of drawing a suitable diagram must be acquired.

In such "key" diagrams, as we may term them, all perspective should be avoided, and a point of view chosen that enables the two sets of lines of flux concerned (those of the original magnetic field and those produced by the current) to be shown in the plane of the paper. These key diagrams should accompany the working diagrams they are intended to explain.

In the case under consideration we see from the key diagram (Figure 52) that the mechanical force is not directly between the material of the conductor and the impressed field, but between two independent magnetic fields, one of which is produced by the current itself, and it becomes another instance of the fundamental property that lines of flux in the same direction repel each other sideways.

It is important to realise clearly that all practical motors are driven by making one set of lines of magnetic flux push against another set.

As we shall make free use of such key diagrams, a few words of warning may be given respecting them. First, they are not intended to be an accurate picture, and only a few lines of flux should be drawn to indicate the direction of the remainder. Second, they only represent the components of the actual field produced by their combination. These fields could not exist as shown with lines of flux intersecting, but we can readily see that the field due to the current weakens the original field on one side, strengthens it on the other, and alters its direction half-way between; hence the actual field, which may be obtained experimentally in several ways, is as shown in Figure 53.

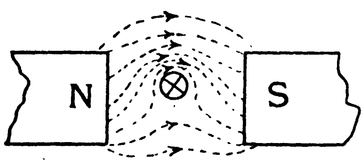


FIG. 53.

This in itself is very suggestive and might be further discussed, but for the present we shall find the diagrams of components more useful.

Returning to our experiment we may notice that a slight modification gives rotatory motion ; the arrangement is then known as Barlow's Wheel.

This is interesting as being a simple illustration of the important principle in question. It consists of a pivoted metal disc which is frequently cut into the form of a star (although this is immaterial, a plain disc works equally well) ; this is supported so that a current may be passed from its centre to its circumference (or vice versa) by means of connection to the bearings and to a mercury cup in which the lower edge dips. Rotation is obtained when a magnet is placed so that the current flows through a magnetic field at right angles to the lines of flux.

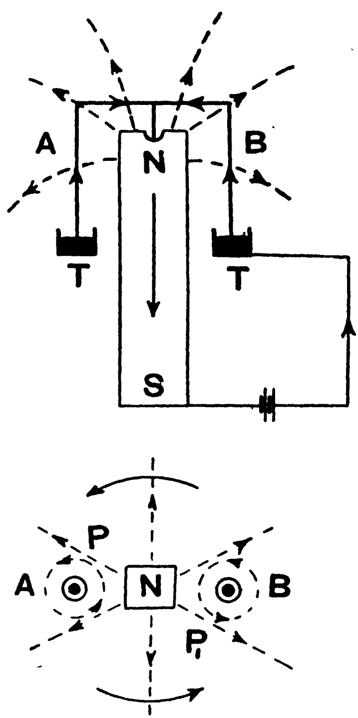


FIG. 55.

The apparatus is shown in Figure 54[1], and the key diagram will, on investigation, be found to be exactly the same as in the previous case, for our suspended wire is now represented by the portion of the wheel between the axle and the mercury cup. The same principle is applied in many other forms of apparatus.

As a further exercise in the use of a key diagram consider the following : A piece of wire bent into the form of three sides of a rectangle is pivoted on the top of a bar magnet (see Figure 55) and rotates when a current is passed in at the two ends and out at the pivot, but not when current is passed in at one end and out at the other.

[1] See Plate III for this figure, which has been placed with motor illustrations because they are the same in principle.

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The two free ends dip into a mercury trough, to which one terminal of the battery is connected, the other terminal being connected to the magnet itself.

In this case it will be convenient to consider the two vertical portions of the wire at A and B. Here the diverging field from the pole is more or less at right angles to the conductor, and in the key diagram the lines of flux may be drawn radially. We see that at the sides P and P_1 the lines of the magnet are in the same direction as the lines around the conductor due to the current, and hence we get repulsive forces which form a couple causing rotation. If, however, the current passed up one side and down the other, one of the forces would be reversed and the two would oppose each other.

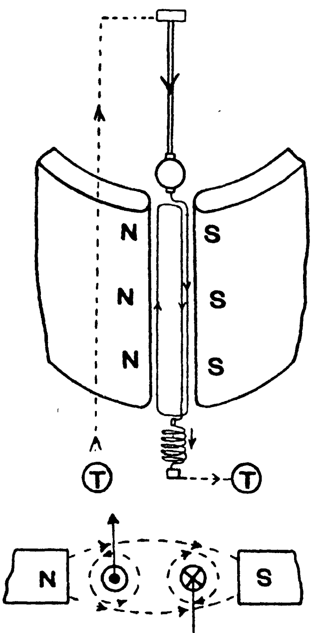


FIG. 56.

Another instance is afforded by an ordinary carbon filament glow lamp run with an alternating current; if a bar magnet be brought near the bulb the filament is thrown into violent vibration and soon breaks. Here the conductor is flexible and the direction of force is reversed many times per second. With continuous current no such effect will be noticed, the filament being merely displaced from its normal position by a probably imperceptible amount.

As a final example of the motor principle we may consider the "suspended coil" type of galvanometer. This takes many forms, but the essential feature in all is a coil of wire suspended in a strong magnetic field in such a way that a current can be passed through it, and at the same time it is quite free to move. In the Ayrton-Mather type a rather long narrow coil is suspended by a fine highly elastic strip of phosphor bronze and

connection is made at the bottom by a delicate spiral of the same material. The position when no current is passing is as shown in Figure 56; the key diagram shows that when a current flows there will be repulsions between the two sets of lines which will constitute a couple, and produce rotation until the moment of the deflecting couple is balanced by the torsion of the strip suspension. In this way by using a coil of many turns of fine wire placed in a strong magnetic field and using a mirror instead of a pointer to make the motions of the coil visible, a very useful galvanometer is produced which will easily show a deflection with a current of one-millionth of an ampere, and may be made much more sensitive if necessary. Its chief value, however, is not due to its sensitiveness (since other types of galvanometer can be made to excel it in this respect), but depends upon the fact that it is practically unaffected by the presence of magnets or masses of iron in its vicinity.

In the cases of the production of mechanical forces so far considered in this chapter, one set of magnetic lines has invariably been produced by a magnet. The presence of an

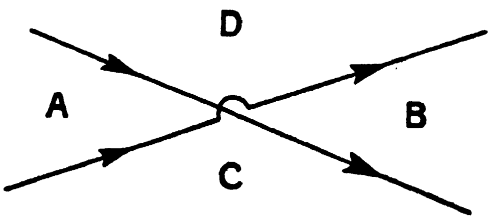


FIG. 57.

iron magnet is not, however, essential, and many cases occur of the production of mechanical forces between current-carrying conductors when no iron is present. Under normal circumstances the forces produced under such conditions are small, but when currents are heavy (as under short-circuit conditions) the forces may be very considerable. The occurrence of forces of this nature between two parallel conductors has already been considered on page 16, but in many cases the two current-carrying conductors will not be parallel but at an angle as shown in Figure 57. Considering the regions

A and B, we see that essentially the currents tend towards parallelism, and from what has been said we should expect attraction between the conductors to result or, what is really equivalent, we should expect repulsion in the regions marked C and D. We may in such cases express the laws of attraction and repulsion as follows: When two currents both flow towards, or both flow away from, a point there will be attraction, while when one current flows towards a point and

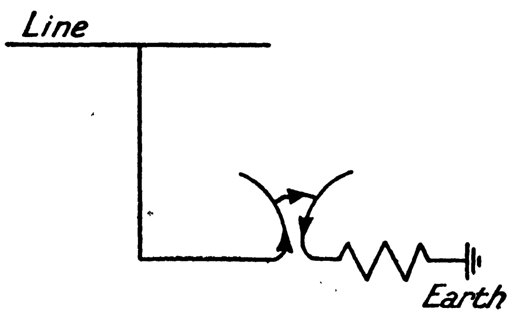


FIG. 58.

the other current flows away from the point, there will be repulsion.

Forces between current carrying conductors (no iron being present) are usefully employed in ammeters and voltmeters of the electro-dynamometer type and also in the arcing horns sometimes employed in connection with spark gaps used as lightning discharge devices. A simple device of this kind is shown in Figure 58, and the mode of action is as follows:—When, owing to a lightning discharge or other cause, the voltage between line and earth becomes excessive, a discharge takes place between line and earth across the gap between the horns which is of carefully adjusted length. Unfortunately, when the discharge has been started, there is a tendency for it to be continued by the ordinary line voltage. We see, however, that the repulsion between the currents in the lower parts of the horns and the current in the horizontal arc will give rise to forces which will tend to drive the arc upwards. This causes an increase in the length of the arc which ultimately becomes unstable and breaks, thus clearing

the gap which is then ready for the next occasion when an unduly high voltage develops between line and earth. It should be mentioned that the effect of the magnetic action is assisted by the natural tendency of the arc to rise, due to thermal reasons.

Many cases are on record where the forces between current-carrying conductors have proved very harmful. Consider the simple knife switch shown in Figure 59. Current is flowing towards the point A in the contact (and in the stem of the

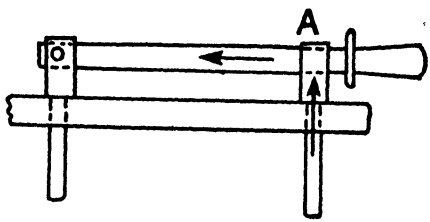


FIG. 59.

contact) and away from the point A in the blade. There is thus a tendency to blow open the switch which, under normal circumstances, would be adequately guarded against by the friction of the contact. Under short circuit conditions, however, the friction of the contacts may be overcome and the switch blown open, thus giving rise to a serious arc and resulting fire risk. In certain cases of the use of knife switches (as in isolating switches in high tension circuits) it is necessary to guard against this possibility by applying a locking device to the blade.

THE GENERATOR PRINCIPLE

We may now consider the first of the two principles mentioned at the commencement of the chapter, namely, the generator principle. Again we must have a conductor in a magnetic field, at right angles (or as nearly so as convenient) to the lines of magnetic flux, only this time instead of sending a current through it we move it through the field.

Suppose we substitute such a galvanometer as that just described for the battery in the first experiment used to illustrate the motor principle, and simply move the suspended

wire quickly between the poles of the magnet (so that it makes contact with the mercury in passing), the result is a very small momentary swing of the "needle,"[1] which is repeated (but in the opposite direction) when the wire is moved back again. The experiment may be more conveniently performed, as illustrated in Figure 60, in which is shown a wire or rod of conducting material, connected to the galvanometer and moved up or down between the poles of a strong magnet.

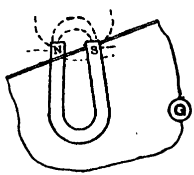


FIG. 60.

The same effect is obtained, i.e. a single transient throw of the needle occurs while the wire is being moved through the field; and the direction of this throw is reversed when the motion is reversed; further, the more rapid the movement the greater the throw. If, however, the rod be held parallel to the line joining the poles, so that when moved upwards or downwards it does not cut the lines of flux, no effect is obtained. In practice this experiment would not be readily performed owing to the difficulty of holding the rod in the correct position. If instead of using a single straight rod, a few turns of wire are connected to a galvanometer, and slipped on or off one of the poles, a greater effect is obtained. This is equivalent to using several rods connected in series, but for the moment it is simpler to think of a single conductor.

We may now state the generator principle as follows:—

If a conductor be moved in a magnetic field so as to cut the lines of magnetic flux, an induced E.M.F. is set up in it whose magnitude depends only upon the rate at which the lines are cut, i.e. upon the number of lines cut per second.

This statement is purposely made concisely, and therefore requires some comment. First notice we say an induced E.M.F. and not an induced current is produced. The distinction is important, for a current can only flow if a possible circuit exists, and if it does flow depends in magnitude upon the resistance of that circuit, and therefore upon the shape,

[1] Long-established usage has made it convenient to refer to the moving part of any galvanometer whatever as the "needle." This term is purely conventional, and when used after does not imply any particular construction.

size, and material of the conductor used; whereas the induced E.M.F. always exists whether there be a current or not, and its magnitude is quite independent of the size and material of the conductor, except in so far as these may modify the number of lines cut in unit time.

Again, if the rate of cutting be uniform through some period of time, the result is a steady E.M.F., but evidently the rate of cutting is often likely to vary very much even in so short a period as one second, and then our statement will refer to the average E.M.F. throughout that time, and not to its actual value at some particular instant, which will depend entirely upon the rate of cutting at that particular instant.

Finally, this independence of material leads at once to a natural and easy definition of the unit of E.M.F., which can be defined as the E.M.F. produced when a conductor moves steadily through a uniform field at such a rate that it cuts one line of magnetic flux per second. This is the "absolute unit" of E.M.F. Its magnitude is small, and the practical unit, termed the volt, is equal to one hundred million absolute units or 1 volt$=10^8$ absolute units of E.M.F.

Many other experimental illustrations of this principle might be given; it is, however, more important at present to aim at clearness of thought rather than to multiply instances, and some confusion is liable to arise at first, from the fact that in some cases we have to think of straight conductors, and in others of turns or coils. As far as possible the difficulties will be explained as they occur, but, speaking generally, we may say at once that it is as well to think of straight conductors when possible, and to regard them as being connected together in various ways by other conductors which merely complete the circuit and take no part in the production of the induced E.M.F. From this point of view one turn is usually equivalent to two conductors in series. For consider a wire rectangle rotating in a uniform magnetic field; it may be regarded as made up of two active conductors AB and CD, connected together by two inactive conductors AC and BD, and as when one active conductor is moving upwards, the other is moving downwards, and vice versa, the two E.M.Fs. are added together. The argument is practically unaltered if we use a ring instead of a rectangle; but it will facilitate matters very

much, when we have numerical calculations to make, if we think of a ring or hollow coil as being "cut" by lines of magnetic flux when the number of lines which thread the ring is altered in any way, with the result that an E.M.F. is set

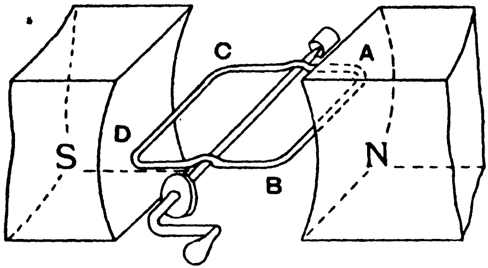


FIG. 61.

up in one direction when that number is increased and in the opposite direction when that number is decreased. We need not trouble, then, as to which are the active parts of the ring.

The great thing is to avoid thinking of lines of magnetic flux as being projected or poked like sticks through the hollow centre; they must be regarded as snapping through from outside to inside and vice versa, and hence inevitably cutting the material of the conductor in doing so.

To contrast the two points of view, suppose that the ring instead of being rotated is dragged bodily through a uniform field at right angles to the lines of flux; the two active conductors are now the portions at the top and bottom of the diagram (see Figure 62), and the E.M.Fs. will both be towards us, since both conductors are moving through the field in the same direction. This means they will be in opposition, no current will flow, and we may say, with regard to the whole ring, no E.M.F. is produced. And we get the same result at once by noticing that the number of lines intersecting the ring is not altered in any way by the motion, for as many as leave on one side re-enter at the other, and hence there will be no resultant E.M.F.

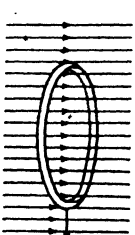


FIG. 62.

The question now suggests itself, how can we, apart from experimental evidence, determine the direction of an induced E.M.F.?

The general problem may be dealt with in the same way as before. Let a conductor be placed, as shown in Figure 63, in a magnetic field. It is required to find the direction of the induced E.M.F., given the direction of motion.

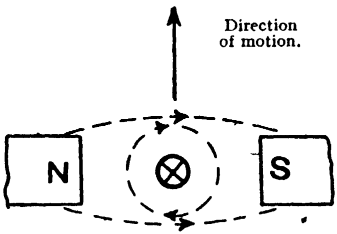


FIG. 63.

Assume the latter to be upwards as in figure, and further suppose that the ends of the conductor are joined by a wire so that a current may flow under the influence of the induced E.M.F. The existence of this current means that a certain amount of energy is expended in the circuit in the form of heat, and as this energy cannot have been produced out of nothing, its source must be looked for in the work done in moving the conductor through the field. In such an experiment the work done is very small, but we can logically infer that it must exist, and that it must be a little harder to move the conductor when its circuit is completed than when it is on open circuit, for no energy is expended electrically in producing merely an E.M.F. It follows that in the former case there must be some extra resistance to motion, and this can only be due to the reaction between the field produced by the current and the original field. Hence the lines of magnetic flux around the conductor must be in such a direction that the pressure exerted upon them by the lines of the original field tends to drive the conductor backwards.

This being done, it is only necessary to mark the conductor with the corresponding direction of current, and this will be the direction of the induced E.M.F., whether there is actually any current or not.

Now take the case of a magnet entering a coil of wire; evidently the lines of magnetic flux are entering the coil from the outside, and in doing so are cutting the turns of wire (see Figure 64).

If a current flows in virtue of the E.M.F. produced by this

motion it must represent electrical energy obtained at the expense of mechanical work. This means the magnet must enter the coil against a repulsive force, and as the induced current will make the coil itself act temporarily like a magnet, it follows that its direction must be such as to produce this repulsion, and we therefore deduce the direction shown in the diagram.

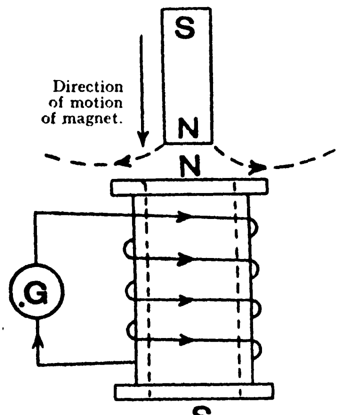


FIG. 64.

The magnitude of the E.M.F. will vary during the motion; reaching a maximum when the rate of cutting is greatest and becoming zero when the magnet is symmetrically placed inside the coil. Further motion in either direction then means that some lines of flux are leaving the coil from inside to outside, and an E.M.F. in the opposite direction is consequently produced.

If, for instance, the relative positions are as shown in the diagram, but the magnet is leaving the coil instead of entering it, then as before work must be done to obtain a current, and so we must reverse the direction of flow in order that magnetic attraction between unlike poles may tend to resist the separation of magnet and coil.[1]

[1] The above method of determining the direction of current may be found rather laborious when it is applied frequently, and the following rule, which is founded on the results obtained by the above method, may be found useful: Place the outstretched *right* hand so that the palm is facing the direction of motion of the conductor (relative to the lines) and the thumb is in the direction of the lines of magnetic flux, then the fingers indicate the direction of the induced E.M.F. in the conductor.

In a similar way we have a handy rule for the motor principle: If the outstretched *left* hand is placed so that the thumb is along the direction of the lines of magnetic flux and the fingers in the direction of the current, then the palm faces in the direction of the force acting on the conductor.

As to the actual value of such rules there is some difference of opinion.

The argument used above, based on the principle of "Conservation of Energy," applies equally well to any other form of circuit, or to solid lumps of metal. In a more general form it is embodied in **Lenz's Law**, which for our purpose may be expressed by saying that *whenever induced currents are produced by motion, the reactions set up are always in such directions as to tend to stop the motion which produces them.* It is merely a familiar mechanical law in another guise; if you try to push a truck or start a fly-wheel, you can be quite certain that the reaction set up by its inertia will never assist you, but will always tend to oppose your efforts. Hence it is that when by careless design or inevitable difficulties of construction, portions of metal, bolts, and fittings generally get placed in a varying magnetic field, induced currents will be set up in them which represent a loss of energy, and which, in practical electrical engineering, will directly affect the coal bill.

Induced currents produced in masses of metal are known as "eddy currents," or sometimes as "Foucault currents," although they were not discovered by Foucault.

If a sufficiently powerful electro-magnet be available, the resistance to motion due to induced currents in masses of metal can readily be demonstrated, for it is appreciably felt when a sheet of metal, such as copper, is moved rapidly between the poles. With moderate power it can be shown distinctly by attaching a thread to a copper disc (the shape is immaterial), twisting the thread and allowing the disc to spin as the thread untwists; if, while in rapid motion, it is lowered between the poles of a magnet, it at once slows down, regaining speed, however, when removed from the magnetic field (see Figure 65).

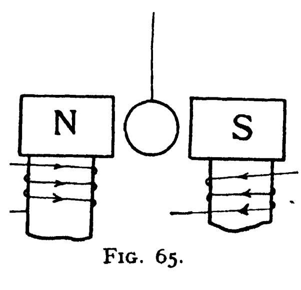


FIG. 65.

The distinguishing peculiarity of this kind of retarding force, or "magnetic drag," is the fact that it varies as the speed: the more rapid the motion of the body the greater is the instantaneous resistance to that motion, while a slow moving body is almost unaffected by it.

There are so many practical applications of this effect that it is quite unnecessary to multiply lecture-table experiments in illustration. For instance, the production of induced currents is made use of in checking the motion of a tram-car by the " electrical " or " emergency " brake.

This is dealt with more fully on page 225, but we may note in passing that such a brake cannot actually stop a car on an incline, and will also be ineffective for rapid retardation at slow speeds. It must be supplemented by a hand brake to " hold " the car after the electrical brake has performed its work by quickly reducing the original speed.

More useful instances at present are to be found in various electrical instruments. Take the case of the galvanometer already described. This will be found inconvenient in practice (for some purposes), because when set in motion the moving part oscillates for a long time before coming to rest. If a current is passed through the galvanometer it is desirable that the coil should at once take up the steady position corresponding to that current and stop there, returning equally promptly to zero when the current is stopped.

Any instrument which does this is said to be " dead beat." In the case in question the desired result may be obtained by slipping over the coil a thin metal tube, preferably of silver on account of its high conductivity. This moves with the coil in the strong magnetic field due to the fixed magnet, and currents are induced in it by the motion which are quite independent of the working current in the coil, and which, by their reactions, check all sudden movements of the coil, at the same time leaving the coil quite free to take up any definite final position. Its oscillations are then powerfully " damped," and the instrument is more or less " dead beat."

Without this contrivance the coil once in motion has to swing until the energy of motion it possesses is slowly converted into heat by air friction, and by want of perfect elasticity in the suspension; by adding the metal tube the same energy is more rapidly converted into heat by an initial conversion into electrical energy. In any case, however, the coil can be rapidly brought to rest, if the terminals of the instrument are connected together by means of a wire, for then induced currents are set up in the coil itself. To some extent this is true for any galvanometer.

We shall find as we go on similar methods of damping applied in various ways. If it be required to steady the action of any moving part, it is only necessary to attach to it a suitable sheet of metal moving in a strong magnetic field, usually provided by a small auxiliary magnet.

Finally there is the converse side to our argument. Whenever, as in the case of the armature of a dynamo, a mass of metal has to move in a magnetic field without wasting energy in eddy currents, it must be built up in such a way that there is no circuit in which a current can flow, i.e. it must be "laminated," or built up of thin separate slices insulated from each other by a layer of paper or varnish or even merely by rust and scale.

In this way eddy currents can be reduced to a minimum, although they can never be wholly eliminated.

CHAPTER VII

INDUCTION COILS AND TRANSFORMERS. SELF-INDUCTION

SO far we have mainly considered the motion of a conductor in a stationary magnetic field, but evidently either or both may move; all that is wanted is relative motion. Again, if we can make lines of magnetic flux move by themselves, there need not be motion of ordinary matter at all.

The case of induction between parallel circuits is of this latter kind. Experiment shows that if conductors AB and CD are placed near one another as in Figure 66, there is an induced E.M.F. in CD while the current is starting in AB, and another in the opposite direction while the current is stopping, that is, when the circuit containing AB is broken. No effect is produced in CD by a current in AB, whatever its magnitude, so long as it is steady, but any sudden variation in its strength produces a corresponding momentary E.M.F. in CD. To understand this we have merely to draw a diagram showing the conductors in section. We see that as the current starts in AB a magnetic field must come into existence in the space around it. This is not the place to discuss in detail the method of its formation, and for our present purpose it will be best to think of the lines of magnetic flux as expanding outwards as closed curves until the current becomes steady. Obviously the moving lines of flux will cut the conductor CD, setting up an induced E.M.F. whose direction remains to be determined.

This is done by noticing that starting a current in AB is equivalent to very quickly moving a similar conductor carrying a steady current, from a very great distance up to its present position. The field produced by the induced current in CD (if allowed to flow as in the diagram) will, by its reaction, tend to stop such a motion, and therefore we have only to draw

a line of flux round C and mark it in such a direction so as to produce a repulsion between the conductors, in order to determine the direction of the induced current, and consequently of the induced E.M.F.

In this way we find the induced E.M.F. in the " secondary " circuit CD is in the opposite direction to the " primary " current in AB, whilst the latter is rising, and an obvious extension of the argument shows that it will be in the same direction whilst the latter is stopping (or, if the current is steady, when AB is moving away from CD).

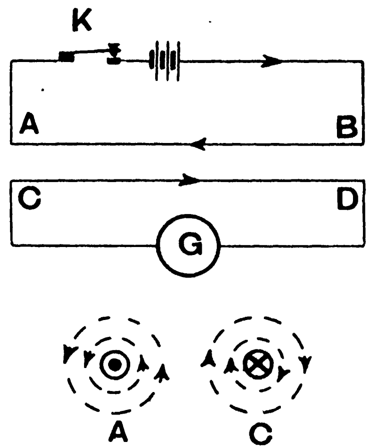


FIG. 66.

Two points may here be noted. In the first place, if the magnetic field does spread out as we have suggested when a current is started in a conductor, it must disturb in some way the whole surrounding space to an infinite distance; and the further question arises, as to whether the propagation is instantaneous, or possesses a definite velocity. Such questions have led to the electromagnetic theory of light and wireless telegraphy.

Again, we see that as no actual motion of matter has occurred, the energy of the induced current in CD has been derived in some way from the energy supplied to the primary circuit AB. This fact is very important, and will be dealt with in due course.

Returning to our experiment, it is in practice inconvenient to deal with long lengths of straight wire, and the same end is achieved if we wind the two conductors into separate, but concentric, coils.

It is customary to refer to these as " primary " and " secondary " respectively; but their functions are quite interchangeable.

Consider, therefore, any coil of wire of solenoid form

connected in series with a cell and a contact key for "making" and "breaking" the circuit; on closing the circuit a magnetic field is produced which remains unchanged (unless the current strength is varied) until the circuit is broken, when it disappears; and by employing some device for rapidly interrupting the primary circuit this magnetic field is continually appearing and disappearing.

Let this primary coil be placed inside (for convenience, not of necessity) another separate coil, well insulated from the first. Then this "secondary" coil will have produced in it an induced E.M.F. in one direction, while the lines of magnetic flux are appearing, and another, in the opposite direction, while they are disappearing. The important point to grasp clearly is that the magnitude of these E.M.Fs. depends only upon:—

1. The number of lines of magnetic flux which appear and disappear.
2. The time in which they appear and disappear.
3. The number of turns in the secondary.

It therefore only depends indirectly upon the E.M.F. in the primary circuit.

All this might be more simply expressed by stating that the induced E.M.F. at any instant, in a given secondary, only depends upon the rate of cutting of lines at that instant.

It is important to notice that if the primary is operating with a fixed current and contact breaker, 1 and 2 are fixed, whereas 3 is a variable entirely at our disposal, and hence the secondary E.M.F. may have any value we please, great or small.

If a very high E.M.F. is required, we must use many turns in our secondary, of course reducing the section of the wire at the same time in order to get the turns in a reasonable space. If a low E.M.F. is wanted, then the secondary should consist of a few turns, and we may with advantage increase their cross-section.

The usefulness of nearly all applications of induction coils and transformers depends upon this one property of enabling any required voltage to be obtained from any given initial voltage.

If the secondary E.M.F. be allowed to produce a current

and thus expend energy, we can be quite certain that the watts thus expended cannot be greater, and in fact must be less (on account of heat losses, etc., occurring in the coils) than the watts supplied to the primary, and therefore, supposing the latter to be constant, a high secondary voltage implies a small current, and vice versa. Beginners are apt to confuse themselves by thinking of the induced current first; the correct method in all cases is to think of the induced E.M.F. and then the current will take care of itself.

So far we have not mentioned an iron core; if this is used it in no way alters our argument, but it enormously increases the magnetic flux produced by a given primary current, and thus greatly reduces the size of the apparatus for a certain output.

We may classify the various practical forms of induction coils as follows, and in this work it is only possible to briefly outline their leading features:—

1. Induction coils for giving shocks.
2. Induction coils for giving sparks.
3. Transformers.

INDUCTION COILS FOR GIVING SHOCKS

In the first group we are dealing principally with toys, or specialised apparatus for medical purposes. Without going into the complicated question of the behaviour of the human body as a conductor, it is sufficient to say that an exceedingly small current will give a perceptible shock, especially when rapidly (but not too rapidly) interrupted; also in order to send this current through the high resistance of the body, a fairly high E.M.F. is required, which may be obtained by means of a battery of cells or other means, but which is readily obtained by means of a small induction coil worked by a single cell.

At the same time this voltage is not great enough to call for excessive precautions in the way of insulation, and hence a very simple construction will give satisfactory results.

It is usual to employ an automatic circuit breaker operated by the magnetism of the core, similar in principle to the contact breaker of an ordinary trembling bell.

The strength of the shock is regulated by means of a metal

tube sliding over the core; this latter is really another coil of one turn, and does not operate by shielding the secondary proper from the lines of magnetic flux, as often erroneously supposed, but by setting up a more or less opposing flux of its own.

The construction of such a coil is shown in Figure 67. It will be noticed that the end of the primary is joined on to the beginning of the secondary (see the small key figure) and the

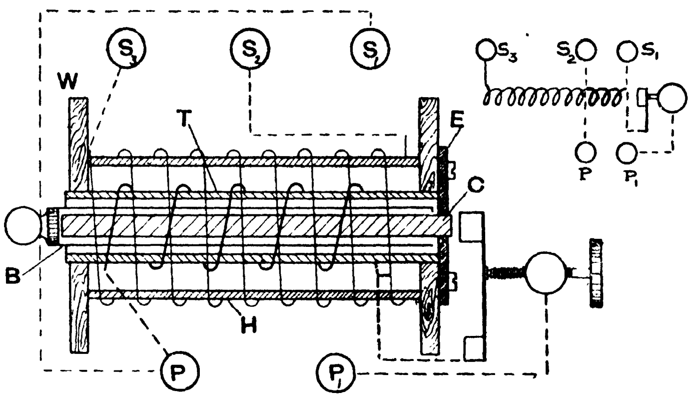


FIG. 67.

junction is brought out to a terminal S_2; this enables three strengths of shock to be obtained (see page 103).

The method of connection indicated in the figure is also used in coils for motor ignition, and is permissible generally for moderate voltages; insulation difficulties make it very unsuitable for spark coils proper.

The bobbin may be made by fitting wooden ends (W) on to a pasteboard tube (T), in which slides a brass tube (B).

The iron core (C), which may be solid, is sweated or fixed into a brass plate (E), and this plate is screwed to one of the ends of the bobbin.

The primary and secondary are insulated from each other by the insulating layer H.

Such a construction is mechanically quite strong enough for a small coil.

SPARK COILS

The second group, or spark coils, have become of commercial importance through their application to X-Ray work, wireless telegraphy, etc. The very high voltage required to start a spark in air (something like 70,000 to 100,000 volts for a one-inch spark) means that the greatest precautions

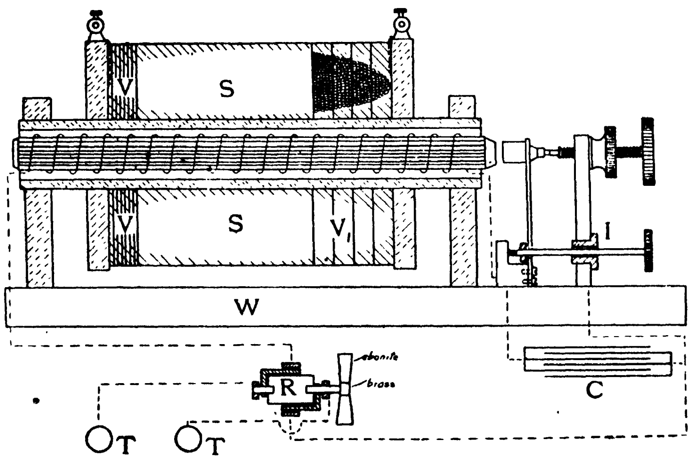


FIG. 68.

S, Space occupied by secondary winding. V, Vertical insulation. V_1, Vertical insulation, drawn further apart to show wire more clearly. W, Wooden base. C, Condenser. R, Primary current reverser (actually mounted on base W). I, Insulating washer. T, Primary terminals.

must be taken to insulate adequately the secondary turns from the primary, and from other secondary turns which may be at a very different potential. To obtain this high voltage not only are many secondary turns required, but especial pains must be taken to make the primary field disappear very rapidly in order to obtain the greatest possible rate of cutting of lines of flux.

To this end the core should be made of iron wire, not so much to prevent heating through eddy currents, an effect which in this case would be relatively unimportant, as to facilitate the rate of gain or loss of magnetism (for eddy

currents always exert a magnetising influence of their own which is in opposition to the desired change).

Again, the primary circuit must be broken as suddenly as possible, and although the ordinary vibrating contact-breaker, provided with a condenser as a shunt to the spark gap, is largely used for small coils, it has been largely superseded by more elaborate mechanical "breaks" for larger coils.

The construction of a modern high-class coil to give sparks of 6″ in length and upwards is shown in Figure 68. The iron core, wound with two or three layers of stout wire forming the primary, is enclosed in an ebonite tube about ¼″ thick, and preferably considerably longer than the secondary coil. This latter is always wound in sections, which can be insulated and tested separately before being slipped into place on the ebonite tube; this construction ensures that the P.D. between adjacent conductors shall always be small. For if the wire were to be wound in a continuous horizontal layer from one end to the other and then back again, many thousands of turns would probably be in circuit between the first turn of one layer and the turn lying immediately above it in the next layer, and thus a very great P.D. might exist between adjacent conductors, and a correspondingly great strain would be placed upon the insulation. To avoid this, the wire should only be wound a short distance horizontally before it returns on itself.

To this end the fine silk-covered wire (about 36 gauge) is drawn through melted paraffin wax and wound on a suitable metal bobbin, with removable sides, into a number of separate coils, each perhaps $\frac{1}{16}$″ thick, and varying in depth from about ½″ for the end coils to nearly the full depth of the secondary at the middle.

Each coil therefore forms a thin vertical slice of the winding (something like a narrow roll of tape).

The wax holds the turns sufficiently together to enable them to be removed from the bobbin, and then each is placed between two circular discs of insulating material and the whole sweated together with paraffin wax.

The result is a hard compact coil which can be handled without injury. Each section is then paired off with an exactly similar coil, the two inner ends are soldered together

and pushed up out of the way between the discs, then both are sweated together by a warm iron and paraffin wax, and we now have a double coil with all the wire in series and both free ends on the circumference, this double coil constituting a unit of the winding.

When a sufficient number, perhaps a hundred or more, of these double coils have been prepared, each may be separately tested for continuity and insulation, the latter preferably by making it act as a small secondary. For instance, it may be slipped by itself over the tube containing the primary, and the latter excited until the coil to be tested gives, say, a $\frac{1}{4}''$ or $\frac{1}{2}''$ spark between its end wires, which will be a greater P.D. than it will ever be required to give in actual use.

These unit coils are then slipped over the ebonite tube in proper order, those at the ends containing little wire and being of greater internal diameter than the tube, the space between being filled up with wax or other insulating material. When all are in place, and screwed up tightly between the end flanges (also of ebonite), the various ends may be soldered together and pushed between the discs out of the way, testing at each step for continuity with a cell and galvanometer.

Finally the whole external space may be filled up with paraffin wax run in hot, which solidifies into a solid cylindrical block. This can be covered with thin sheet ebonite by way of a finish and the ends of the secondary connected to suitable terminals fixed to the ebonite bobbin ends.

In this way a coil of any size may be built up which will stand enormous differences of potential without breaking down. The greatest danger is that of leakage to the primary; the tendency to do this is greatest at the ends of the secondary. In the middle of the winding the potential is zero, and in fact the middle point might be earthed with impunity.

It is on this account that greater thicknesses of insulation are used at the ends and the tube containing the primary prolonged beyond the secondary.

In the figure an ordinary contact breaker with regulating screw to adjust the tension is shown, although this is not an essential feature of the coil. Any form of current interrupter may be used and may be fitted up independently.

Usual accessories are a condenser in parallel with the spark gap, and a current reverser in the primary circuit. The latter

is merely a simple form of switch, but the former is of vital importance. Without it the spark at the contact breaker is very intense and rapidly wears away the platinum contacts, whilst the spark proper between the secondary terminals is somewhat disappointing.

With a suitable condenser as a shunt to the spark gap the former spark is much reduced and the latter greatly increased.

The explanation of these phenomena is so instructive and its application to alternating currents so important, that it will be well worth while devoting special attention to it before discussing the action of transformers.

SELF-INDUCTION

If we connect two short pieces of wire to the terminals of a primary battery of a few cells and complete the circuit by bringing the ends together, nothing is noticed at the moment of contact, but when separated a slight spark is produced at the moment of "break."

This short circuiting is not very good for the battery and should not be attempted with accumulators.

If we now include in the circuit a fairly large coil of wire such as that used for an electro-magnet, and repeat the experiment, again nothing will be noticed at "make," but the spark at break will probably be found more intense, although the current flowing may have been reduced by the resistance of the coil to a very small fraction of its original value. Finally, if an iron core is placed in the coil, the spark is evidently much more intense, although the current is unaltered.

These experiments show that the strength of the spark which occurs when a circuit is broken is not merely proportional to the current flowing at that instant, but also depends very largely on the amount of magnetism (i.e. the number of lines of flux) produced by that current.

The spark itself is an incipient arc, and indicates the existence of a P.D. across the gap at the moment of break which cannot be merely due to the E.M.F. of the battery, for that is so low as to be absolutely incapable of producing an effect of such intensity; and, moreover, if that had been the

case we should have expected the greatest effect in the first experiment.

Hence we infer the existence of some other E.M.F. as yet unknown, and the inference can be confirmed by a simple modification of the apparatus.

In Figure 69 the same arrangement of apparatus is shown with the addition of two wires (HH) connected to the ends of a coil (C), which may be held by a student while the circuit is made or broken by the key.

Nothing is felt at "make," but at "break" there is a distinct shock which is much increased in intensity when an iron core is placed inside the coil.[1]

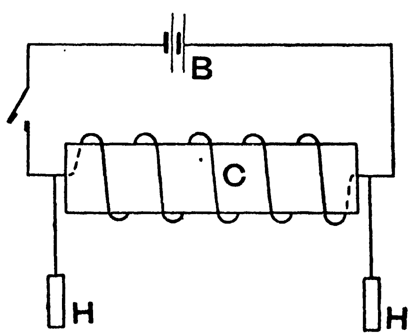


FIG. 69.

As the battery E.M.F. is much too low to give a shock at all, we are again obliged to infer the existence of another E.M.F. whose value depends in some way on the strength of the electro-magnet used. It is called the **E.M.F. of self-induction**, and we shall usually denote it by the symbol E_s.

Before we closed the circuit no magnetic lines existed in connection with it (unless due to some unimportant residual magnetism of the iron core), and a brief fraction of a second afterwards lines are found to exist threading the coil and linked with it. During this time the lines must have been flashing into existence, and as they are always closed curves and not simply poked endways through the coil, they must in doing so have cut the turns of the coil itself.

But when such cutting occurs an induced E.M.F. is always produced whatever the cause of the cutting may be, and this is no exception to the general rule. There is an induced E.M.F. quite independent of the battery E.M.F. which comes into existence during the growth of the magnetic field ; its

[1] It is this shock which is obtained from the terminals S_2 and S_1 in the coil shown in Figure 67.

strength is greatest when the rate of growth is greatest, and it gradually dies away and becomes zero at the instant the field reaches its steady value, in most cases the whole operation taking only a small fraction of a second.

The direction of this "induced E.M.F. at make" has now to be determined. Perhaps the simplest argument which can be used is the following. We have already found in the case of an induction coil that the induced E.M.F. in the secondary at "make" is in the opposite direction to the primary E.M.F., and as the magnetic lines due to the core must during their growth sweep through both the coils in precisely the same direction and in the same way, they must set up E.M.Fs. in the same direction in both. In the secondary this is the induced E.M.F. already discussed, and in the primary it is the E.M.F. of self-induction, which is, therefore, whether there be a secondary or not, in the opposite direction to the E.M.F. producing the primary current.

We have already alluded to the very important idea of a "back" E.M.F. (see p. 66). The usual mistake is to think of it as a "back current." What it really means is, that for a short time after switching on an "inductive" circuit to some source of direct E.M.F., the expression for the current is of the form $I=\frac{E-Es}{R}$, where, taking the particular case of the coil in Figure 69, E is the P.D. we create between its terminals, or the impressed E.M.F., R is its resistance, and Es the induced E.M.F., which has a brief growth and rapid decay. As its very existence depends upon the rise of current, it can never exceed in value the impressed E.M.F., for it would then stop and reverse the current whose growth produced it. What it does is to make the growth of the current more gradual.

Nothing further occurs as long as the current is steady, but when it is interrupted the magnetic lines in their disappearance must move in an exactly opposite direction to before, and thus another induced E.M.F. is set up, this time in the same direction as the impressed E.M.F., and therefore tending to maintain the flow of current after that E.M.F. has disappeared. The value of this self-induced E.M.F. at break depends upon the working conditions.

For instance, if we keep the key A closed and connect

up another key B as a shunt to the battery as shown in Figure 70, then closing the key B practically cuts out the battery without opening the circuit, and the induced E.M.F. due to the disappearance of the field can set up a current in the closed circuit which tends to maintain that field and thus keep it from disappearing instantly. Hence, as the magnitude of the induced E.M.F. depends upon the rate of cutting, this tends to keep down its value.

But when the key B is kept open, and the circuit opened by A, no such gradual dying away of field and current is possible; both must disappear rapidly, and therefore the momentary self-induced E.M.F. may reach a very high value, quite enough to give a very severe shock if a circuit is formed through the body, or to produce a spark across the gap at the moment of interruption.

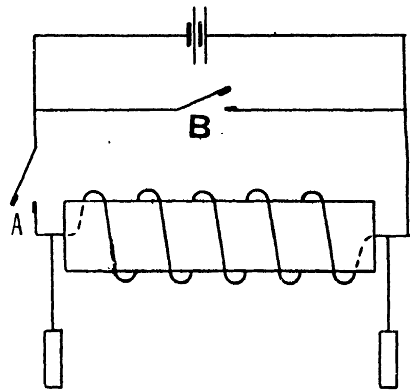


FIG. 70.

In this way it becomes apparent that while the growth of a magnetic field must be gradual (although the actual time taken may be short) its disappearance may be either gradual or extremely rapid.

Applying these ideas to an induction coil, it will be evident that the induced E.M.F. in secondary at "make" must always be less than the corresponding E.M.F. at "break," and we also see the more sudden and instantaneous the "break" the greater the latter E.M.F. will be. Lord Rayleigh has shown this by breaking the primary circuit with a bullet from a rifle. The single secondary spark thus obtained was much longer than that produced by using a pistol, and the latter again was longer than that produced by using an ordinary "break."

Action of Condenser.—Suppose we connect a **condenser** across the two wires marked HH in Figure 69, and then

repeat the operation of making and breaking the circuit. Then we observe that the sparking is much less intense, and under suitable conditions it may almost disappear. The same result is obtained if the condenser be connected as a shunt to the spark gap; in fact the two arrangements are practically identical.

Without the condenser, the P.D. across the spark gap rises very rapidly when the "break" occurs; so rapidly that it reaches the value needful to produce a spark *before* the contacts have time to separate by an appreciable distance, and as a result a comparatively heavy momentary current, due to the E.M.F. of self-induction, flows across the gap and round the circuit.

The presence of the condenser enormously increases the effective size of the conductors forming the two sides of the gap, and the whole area must be charged before the P.D. rises to the sparking value. It is like introducing a large tank in a water system subject to sudden rushes, which must fill up before the water can overflow. In this case the P.D. across the gap rises more slowly and the contacts have separated by an amount great enough to prevent much sparking before the P.D. has reached a very high value. (The effect of the "bullet break" just referred to is essentially the same. It is a method of opening the gap very quickly, even more quickly than the P.D. rises.)

This, however, is not the only effect of the condenser. When it is absent the self-induced rush across the gap is in the *same* direction as the current which was interrupted, which amounts to a prolongation of that current. This retards the disappearance of the field and reduces the rate of cutting, and as a result the self-induced E.M.F. is not so great as it otherwise would be. When this prolongation of the "dying away" period is obviated by the presence of the condenser, the rate of cutting and the induced E.M.F. are proportionately greater. Moreover, the condenser cannot *remain* charged, for it is always short-circuited by a conducting circuit, and therefore it commences to discharge as soon as the charging P.D. begins to fall, thus producing a momentary flow of current in the *opposite* direction round the circuit, which is just what is required to hasten the disappearance of the field.

These facts are well illustrated by the experiment indicated in Figure 71. It is identical with the last experiment except that in addition a lamp L is connected in parallel with the coil and condenser K. The battery voltage should be great enough to make the lamp filament visibly red when the circuit is closed.

On breaking circuit it will be noticed that not only is the sparking suppressed, but that at the same instant the lamp flashes up more brightly. A few tests will show that the E.M.F. induced in the coil reaches a higher value when the condenser is present, and it will be evident that if the coil was provided with a secondary, as in the case of an induction coil, the secondary E.M.F. would also reach a higher value, for it is produced by the disappearance of the same lines of flux. If the capacity is gradually increased it will be found that a certain value gives the brightest flash and that beyond this point a further increase of capacity reduces the flash, although it does not perceptibly affect the amount of sparking at the contact breaker.

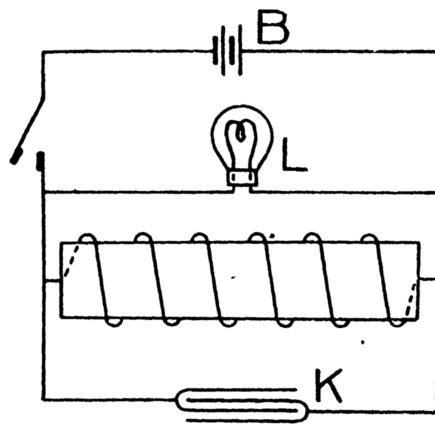


FIG. 71.

It should be noticed that sparking at a contact breaker may be partially suppressed by other methods. For instance, in the last experiment the condenser may be removed and a piece of thin sheet copper bent round the coil to form an outer tube, the edges being soldered together, thus forming a secondary of one turn and low resistance. It will be found to reduce the sparking, although not so perfectly as before. With this arrangement the lamp does not flash up at all and the action is entirely different, the energy previously appearing

in the gap being absorbed by eddy currents in the copper. Particular attention should be paid to the following points :—

(1) All the facts are merely ordinary mechanical principles appearing under a new guise. We are in the position of an engineer who can neither see, hear, nor feel his machinery when it is at rest, but who is liable to be convinced of its existence by being damaged if he gets amongst the wheels while they are in motion. For a circuit in which a current is flowing has marked analogies to a flywheel in motion ; the mass of the wheel being represented by the number of lines of flux produced in the circuit. If the circuit be nearly non-inductive, it may correspond to a light wheel, even if the current be large ; and if very inductive, that is, if it has many turns of wire with iron cores, it may correspond to a very heavy wheel, even if the current be only of moderate strength. And just as it is impossible in practice to start a flywheel at full speed, so it is impossible to start a current at full strength instantly, and the heavier the wheel (or the more magnetism in the circuit) the slower will be the *growth* of speed or current.

The greater the applied P.D., or the greater the effort to start the wheel, the greater will be the back E.M.F., or the apparent resistance it offers, and obviously this must always be in the direction to oppose motion, but can never become great enough to reverse that motion. All it can do is to retard its rise. When the wheel has reached its final and steady speed nothing further need occur until that speed varies, but when we try to stop it another self-induced E.M.F. or reaction is perceptible, which tends to prevent its being stopped.

But whilst we cannot by any means whatever get that wheel started suddenly, we have various means at our disposal for stopping it. We may simply remove the driving power, and let it stop gradually and without shock or we may pull it up by jamming a massive iron bar through the spokes. This latter plan is effective enough, and the consequences will depend upon whether the wheel is a paper toy or an engine flywheel.

Similarly in the electrical circuit we may either stop the current gradually or suddenly ; if the current is stopped suddenly (as we deliberately do in the case of a " spark "

coil) we get the maximum effect in the form of a high-induced E.M.F. both in the coil itself and also in the secondary.

And although there is nothing perceptible to the sight, such actions as opening the shunt circuit of a dynamo in operation, or a circuit in which a long string of arc lamps is being run in series from an "arc lighter," are operations of the same kind as the violent stopping of a flywheel, or the opposing of a brick wall to a locomotive, and the consequences may be equally disastrous, the sudden strain due to the self-induced E.M.F. breaking down the insulation somewhere just as the locomotive "sparks" through the wall.

(2) Evidently the above is a necessary consequence of the fact that a rotating wheel or moving body represents a store of energy which must be supplied to it during the start and which is given out again during the stoppage. In the case of electricity this energy does not belong to the current, but to the magnetic field produced by it. Hence the current at starting does work outside itself in forming this field, storing up energy which is not lost to the circuit in ordinary cases, for it is paid back again during the stoppage. It will become apparent as we go on that a current can only do work (other than heating a conductor on account of its ohmic resistance) by flowing against an opposing E.M.F., being of course impelled by a yet stronger impressed E.M.F., and we shall gradually acquire the habit of inferring whenever such a back E.M.F. is found to exist, that energy is being transferred from the circuit and given up in some way to outside bodies.

We have been thinking thus far about the starting and stopping of ordinary direct currents. In the case of alternating currents self-induction becomes of much greater practical importance. The impressed E.M.F. now rises gradually to some definite value, then falls gradually to zero, again rises to the same value as before but in the opposite direction, and again falls to zero. This constitutes one complete cycle or period, and the number of complete cycles per second, usually fifty, is called the "frequency."

The current produced of course rises and falls in a similar way and has the same frequency. When we speak of a given number of alternating volts and amperes we mean the steady readings such E.M.Fs. and currents will give on suitable instruments.

Our imaginary flywheel is now receiving a series of oppositely directed impulses and is moving backwards and forwards like the balance wheel of a watch.

If the circuit is non-inductive (corresponding to a very light flywheel) there is no E.M.F. of self-induction, and consequently we should expect the current in such a circuit to follow Ohm's Law; this reasoning is true in the case of a load of incandescent lamps.

If the circuit is inductive (corresponding to a heavy flywheel) the current must start and stop gradually, and the amplitude of swing will be less for a given impressed E.M.F., and the circuit will be continually absorbing energy (as the current increases) and giving it out again (as the current falls).

An inductive circuit behaves then as if there were a back E.M.F. opposing the impressed E.M.F., and it is evident that this becomes as real and definite as the impressed E.M.F., only it cannot be measured on a voltmeter.

Thus there are two alternating E.M.Fs. to be taken into account before the current can be calculated by Ohm's Law. If we take both into account, then Ohm's Law holds good, the current at any *instant* being given by

$$i=\frac{e \pm e_s}{R},$$

where e and e_s denote the actual values of the impressed and induced E.M.F. at the instant under consideration.

Such instantaneous values cannot be read on instruments, and the relation between observed values is rather more complicated and will not be dealt with at present. It is sufficient to point out that it is impossible to calculate either the current in amperes or the power in watts by the ordinary method when an alternating current is flowing through an inductive circuit, and the flywheel analogy enables us to see that the more inductive the circuit, the smaller becomes the current for a given impressed E.M.F.

This is easily demonstrated by experiment; for instance, a coil of wire having 10 ohms resistance was placed in series with an ammeter and connected up to 100 volt mains (alternating E.M.F.) and the current was found to be 4 amperes, whereas by Ohm's Law it should be 10 amperes. When an

iron wire core was inserted the current fell to 2 amperes, and when this core was bent round so that the ends met it became less than 1 ampere.

It follows from this that whereas we can only regulate the strength of a steady or direct current, supplied at constant potential, by adjusting the resistance in circuit, we may, in the case of alternating currents, either employ that plan, which is necessarily wasteful of energy, or we may introduce self-inductance, which need not be wasteful.

A "choking coil" is a contrivance for this purpose. Any kind or shape of coil on an iron core will "choke," but the term more especially denotes a coil with laminated iron core (preferably with open magnetic circuit) purposely made of stout wire to have low resistance so that the I^2R loss shall be negligible. Frequently the core is movable, and then the arrangement affords a very convenient method of adjusting the strength of a current.

Gradually inserting the core in such a coil is exactly like gradually increasing the mass of a wheel.

The amplitude of swing due to a given series of alternating impulses becomes steadily less although but little power is expended.

Having obtained clear ideas about self-induction, we are now in a position to discuss the subject of transformers.

TRANSFORMERS

In this third group we have the induction coil specialised into a form suitable for the commercial transformation of energy. The great difference from the previous groups lies in the question of power; the largest induction coils of the previous types are only supplied with quite small amounts of power, and it is relatively unimportant how much they waste if in other respects they answer their purpose, whereas transformers may be required to deal with loads of any magnitude, and above all things they must do it efficiently. The first thing to do is to get rid of the contact breaker, which would be fatal to success on the engineering scale; this is done by using alternating currents, and then the induction coil becomes a transformer.

Although essentially the same in principle, their purpose

is different, and the best design for one is not the best design for the other. In the spark coil everything is sacrificed to the production of an enormously high E.M.F., the straight iron core with open magnetic circuit and the sudden break being admirably suited to this end. Such a coil may of course be excited with an alternating current; it then gives a very much shorter (perhaps 1″ instead of 8″ or 10″) although hotter spark.

The spark coil again is solely intended to "transform up" (from low voltage to high voltage), whereas a transformer is more often used to transform "down" (from high to low voltage), although it will serve for either purpose indifferently.

For instance, if designed to transform "up" from 100 to 2000 volts, it is equally suitable for transforming "down" from 2000 to 100 volts. It must be efficient (i.e. it must produce in the secondary circuit nearly as many watts as are taken into the primary) and it must be self-regulating, that is, the watts taken in by the primary must vary automatically with the watts expended in the secondary circuit.

To this end, for reasons which can scarcely be appreciated at this stage in our progress, a "closed" magnetic circuit is used for the core. Hence a transformer in its simplest form consists of two independent coils on a closed and laminated iron core. Innumerable variations in design are possible, and in many cases the advantage which one may have over another in cost of construction, efficiency, etc., can only be ascertained by careful calculation. As in most other cases, however, the general tendency is towards a certain uniformity of type. Remembering there are always two closed circuits, the path of the lines of flux and the path of the current respectively, we can conveniently distinguish two general forms.

1. Those in which there is a single path for the lines of flux, which is usually much longer than one turn of the winding, known as the "Core" type.

2. Those in which there are two paths for the lines of flux, each usually much shorter than one turn of the winding, known as the "Shell" type. In the first the iron core is imbedded in the coils, and in the second the coils are imbedded in the iron core, or we may express it by saying that in the

core type the coils are wrapped round the core, and in the shell type the core is wrapped round the coils.

The core type is now very largely used and has practically driven out the second form. This is mainly on account of the facilities it offers for repairs, etc. The appended diagrams will show that the coils can readily be removed and replaced by taking off the "yoke" at one end, whereas to get at them and replace them in the shell type requires long and tedious labour. It is unnecessary here to discuss minutely the respective merits of these designs; it is our business at present to realise as clearly as possible their behaviour in practice and their sphere of usefulness, leaving their more exact study for a later stage. We may, however, in passing, point out their relation to the "induction coil."

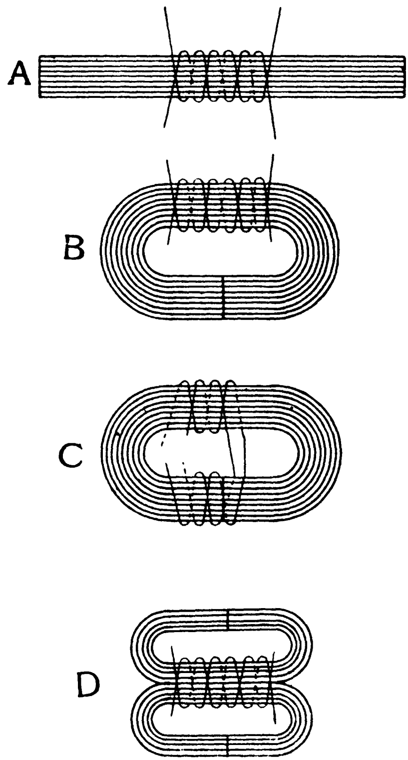


FIG. 72.

Suppose the straight iron wire core of such a coil is made considerably longer than the space occupied by the windings as at A in Figure 72. Then if we bend it round sideways as shown at B in the same figure until the two ends meet, the result is a closed iron circuit. Obviously we may now save space by putting half the windings on each limb, the result being a transformer of the "core" type as shown at C.

We may, however, bend half the core round one way and

the other half round the other way as at D, and if we make the dimension of the core big in a direction at right angles to the paper, we get a transformer of the "shell" type.

In this type the two windings are wound and insulated separately in the form of long flattened coils. These are placed side by side or, better, one over the other, and iron stampings placed over them as shown in Figure 73. Various ways of arranging and shaping the stampings have been used,

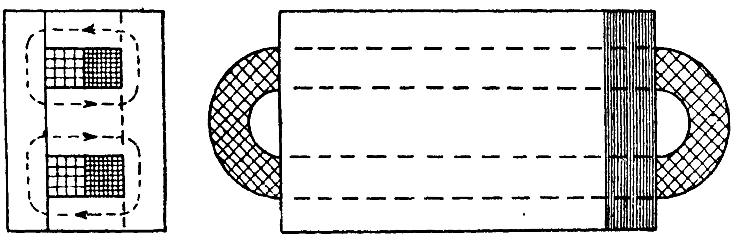


FIG. 73.

and the matter is of real importance in connection with the suppression of eddy currents. In the case illustrated E-shaped stampings are slipped through, alternately from opposite sides, and the circuit completed by the rectangular side strips.

As an example of the core type of transformer, we may take the construction adopted by the Brush Company of Loughborough, to whom we are indebted for the accompanying diagrams.

Figure 74 shows the iron core and frame; it consists of two upright portions to receive the coils, the magnetic circuit being completed at top and bottom by connecting yokes. The cores are built up of iron stampings ·014″ thick, carefully varnished to secure individual insulation and prevent eddy currents. Over the two upright limbs are slipped insulating tubes, on which the low voltage winding of comparatively few turns (in this case the secondary) is wound direct, a half being wound on each limb (see Figure 75). Over this winding other insulating tubes are placed, and the high voltage winding, consisting of many turns of wire, divided up into sections (each of which is wound and insulated separately),

FIG. 74

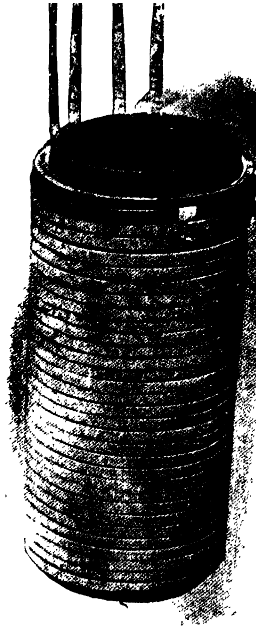


FIG. 75

is slipped over them as seen in Figure 76, a half being on each limb.

This subdivision keeps down the P.D. between successive layers and facilitates repairs; the finished transformer (without protecting casing) being as shown in Figure 77.

Both windings are baked in a vacuum oven to thoroughly expel moisture. Between the primary and secondary windings is an earth-connected metallic shield, which in case of accident keeps the high voltage out of the low-voltage winding.

It might naturally be thought better to put the primary on one limb and the secondary on the other, as such construction would lend itself to efficient insulation; practically, however, this quite alters the working, owing to what is called magnetic leakage, and it is absolutely necessary to mix the winding as much as possible. Without attempting to explain matters at this stage, it may be said roughly that each coil tends to produce a magnetic field, but the two fields oppose each other, and there is always a tendency for some of the lines due to one coil to take a path which misses the other coil, an effect which can only be reduced to a minimum in the above way.

We have now briefly to explain the working of a transformer. Let the primary be connected to alternating current mains kept at a constant voltage, and first let the secondary be on open circuit. Then the primary acts as a very effective "choking coil," and an extremely small current flows, although the ohmic resistance is quite low and the impressed E.M.F. may be high.

The magnetic field produced by this current, as it appears and disappears, cuts both the primary and secondary, and sets up in them induced E.M.Fs., that in the primary being the E.M.F. of self-induction already discussed, and to which the choking effect is due, and that in the secondary the E.M.F. required for the load.

As the rate of cutting per turn is exactly the same for both coils (assuming that none of the primary lines misses the secondary, an assumption nearly but not quite true), those induced E.M.Fs. must be to each other in the ratio of the number of turns in the coils, or we may write :—

$$\frac{\text{E.M.F. of self-induction in primary}}{\text{Secondary E.M.F.}} = \frac{\text{Number of primary turns.}}{\text{Number of secondary turns.}}$$

In a well-designed transformer this E.M.F. of self-induction is almost equal (and opposite) to the impressed E.M.F., and therefore we have very nearly—

$$\frac{\text{E.M.F. impressed on primary}}{\text{Induced E.M.F. in secondary}} = \frac{\text{Number of primary turns.}}{\text{Number of secondary turns.}}$$

It must be remembered that this relation does not determine the actual number of turns in either coil. This must be settled independently. For instance, a transformer intended to transform "up" from 100 volts to 2000 volts will have twenty times as many secondary turns as primary, and will serve equally well to transform "down" from 2000 volts to 100 volts if we now use the coil with most turns as primary, but it must not be assumed that it will also be suitable for transforming from 200 volts to 4000 volts, or vice versa. In this case, although the ratio of the turns is exactly the same, the number in each coil would need to be increased, and in fact a new design required (unless the total load in watts happened to be exactly the same as before, and then doubling the turns and halving their sectional area would meet the case).

If now the secondary circuit be closed on a "load" so that a current may flow, it will be found that the primary current automatically increases or decreases as the secondary current increases or decreases, and in this way the power taken from the source of supply adjusts itself to the load. The ratio of the two currents will be nearly the inverse ratio of the volts, that is, if we get a higher secondary voltage we get a smaller current, and vice versa. This automatic self-regulation in the primary is bound to be more or less obscure until the student is ready to deal with the mathematical theory of a transformer, and it is only possible at present to deal with the matter in a very general way. Now the chief opposition to the voltage applied to the primary is provided by the induced back voltage which is set up by the alternating flux in the core. Indeed we may say that not only at no-load, but also at any magnitude of load, this core flux must be of such magnitude and phase[1] that the induced E.M.F. in the

[1] As stated on p. 233, the word phase, used in connection with an alternating quantity, is employed to indicate the part of the cycle which the quantity is passing through at a particular instant. In actual problems it is the relative phase of two or more quantities that is of importance.

primary at any instant is equal in magnitude and opposite in direction to the voltage applied to the primary.

This statement ignores the losses of voltage in the primary winding due to resistance and leakage which are, however, small in actual transformers. Now the applied voltage does not change in magnitude as the load changes, and it follows, therefore, that the magnitude and phase (relative to the applied voltage) of the core flux must not change as the load alters. When no current is allowed to flow in the secondary, the primary current (which is essentially a magnetising current only) will be small and is of such a value as will give the necessary core flux. When any secondary current is allowed to flow it will tend to disturb the magnitude (and phase) of the core flux. This tendency can be, and is, neutralised by the addition of another component of primary current, called the primary load current, which must be of such magnitude that its ampere-turns are equal to the ampere-turns of the current in the secondary and are in the opposite direction at each instant. Thus we see that any increase in secondary current, caused by an increase in load, is automatically accompanied by a corresponding increase in the primary current. It should be stated that the total primary current will not be the arithmetic sum of the two components (magnetising and load) since these are not, as a rule, in phase with each other. At, or near, full load the primary load current is large compared with the primary magnetising current and we have

primary load current $\times$ primary turns $=$ secondary current $\times$ secondary turns, or

$$\frac{\text{primary load current}}{\text{secondary current}} = \frac{\text{primary current (approx.)}}{\text{secondary current}} = \frac{\text{secondary turns}}{\text{primary turns}}.$$

Further, it will be realised from what has been said above, that if the secondary current is in phase with the secondary voltage, the primary load current will be in phase with the primary applied voltage, while if the secondary current lags behind the secondary voltage, due to the load being inductive (see page 231), so will the primary load current lag behind the primary applied voltage. A short circuit in the secondary

will not only cause large secondary current but will also result in a correspondingly large primary current and both primary and secondary coils may be damaged by excessive currents; fuses in the primary circuit may also be blown when a short circuit occurs in the secondary.

Transformers give us a very simple and very efficient means of raising or lowering the voltage in alternating current systems and thev are of particular importance in connection with schemes involving the transmission of large amounts of power over considerable distances. In such schemes very high voltages (as high as 100,000 volts and upwards) are necessary to escape from the use of prohibitive amounts of copper in the line. Such high voltages cannot be readily generated or directly applied and thus we find step-up transformers in use between the generators and the line and, at the far end of the line, step-down transformers between the line and the load. With direct currents no simple and efficient device having corresponding properties is available and this fact largely accounts for the almost universal use of alternating currents in power transmission schemes.

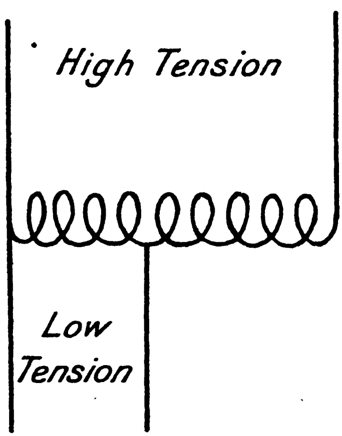


Fig. 78.

THE AUTO-TRANSFORMER

In most cases two quite independent windings are used for the primary and secondary, but this arrangement is not absolutely essential and, in the auto-transformer, only one winding is employed, the whole of the turns being used for the high-tension winding and a portion of the turns for the low-tension winding as indicated in Figure 78. This arrangement has the advantage of being very economical as regards the amount of copper needed, particularly when the ratio of the primary and secondary voltages is near unity, but there is an increased

risk of the high-tension voltage penetrating into the low-tension winding. The use of the device is restricted, therefore, to cases where the two voltages are nearly equal or where no serious result is to be feared should this penetration occur. A well-known example of the use of the auto-transformer is in connection with the lowering of the voltage applied to induction motors during the period of starting.

EFFICIENCY OF TRANSFORMERS

We have already stated that one very important advantage possessed by the transformer is high efficiency and this matter is worthy of some attention, since many points brought out in connection with the efficiency of a transformer are also of importance in connection with the efficiency of other electrical machines. The efficiency of any electrical machine is the ratio of the output to the input, both quantities being expressed in terms of the same unit. Further, it will be clear if to the output we add the losses occurring in the machine, we shall get the input. It is thus possible to write three expressions for the efficiency, these being as follows :—

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{loss}} = \frac{\text{Input} - \text{loss}}{\text{Input}}$$

The losses in a transformer (and in other electrical machines) can be conveniently split into two divisions :—

(1) Those losses which do not materially vary with load and which are known as the fixed losses.

(2) Those losses which vary materially with load and which are known as the variable losses.

In the transformer the fixed losses comprise only those occurring in the iron core and include hysteresis losses and eddy current losses. They are practically constant at all loads because the factors affecting them, such as frequency and flux density, do not materially change as the load varies. The variable losses in the transformer include the I^2R losses in the primary and secondary windings and vary, very nearly, as the square of the output current of the transformer. The magnitudes of the two groups of losses for a 10 kW transformer, having an output voltage of 200, are shown by graphs

in Figure 79, and the curve of total loss is also shown. From these losses it is possible to calculate the efficiency of the transformer at any load in the following manner.

If any value of output current, say 50 amperes, which corresponds to full load on the transformer, be taken, the value of the output is $50 \times 200 = 10000$ watts. The total loss at this load can be read from the curve and is 400 watts and the efficiency at this load is

$$\frac{10000}{10000+400} = \frac{10000}{10400} = 0{\cdot}9615 \text{ or } 96{\cdot}15 \text{ per cent.}$$

In a similar manner the efficiency at any other load can be determined and the graph connecting efficiency with output

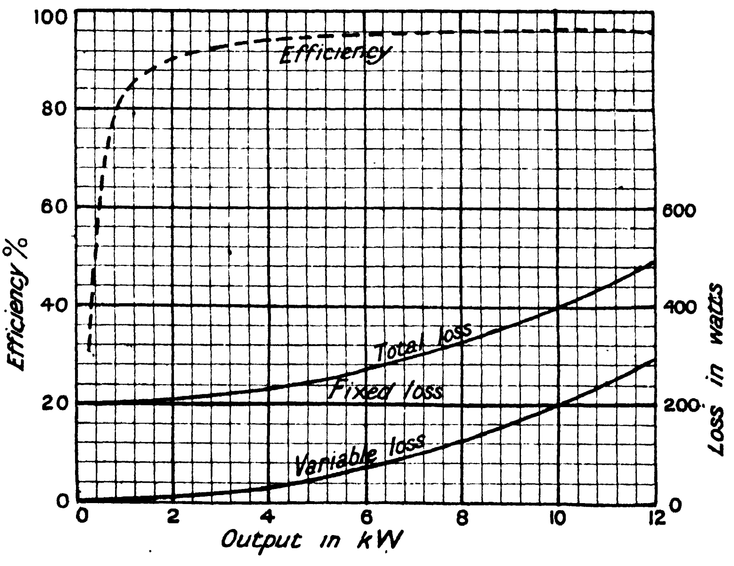


FIG. 79.

current drawn as shown by the dotted line. It is important to note that the transformer has low values of efficiency at low loads due to the large proportion of the fixed losses under these conditions. At very high loads the value of the efficiency

again falls off, this time due to the rapidly increasing magnitude of the variable losses as the currents in the windings increase. For an intermediate load, the efficiency of the transformer attains a maximum value which, as a matter of fact, occurs at the load for which the fixed and variable losses are equal. It is worthy of note that the designer, by varying the ratio of the fixed to the full-load variable loss, can adjust the fraction of full load at which this maximum efficiency occurs. Transformers on a lighting load may work for considerable periods on light load and for only short periods on full load, and for this purpose it is desirable that the maximum efficiency should occur at a point decidedly below full load. On the other hand, transformers which are to work for long periods on full load and but rarely on light load, should have their maximum efficiency in the neighbourhood of full load. The general ideas we have put forward concerning the efficiency of transformers also apply to the efficiency of motors and dynamos, though the matter is then somewhat more complicated owing to the greater variety of losses occurring in such machines.

CHAPTER VIII

CURRENT GENERATORS

WE have now to consider the practical application of what we have termed the "dynamo principle" to the generation of electro-motive force by mechanical means. The essential requirements are (1) a magnetic field, (2) a set of one or more active conductors suitably connected, (3) a particular kind of relative motion of lines of flux and conductors. It is entirely a matter of convenience as to whether the conductors move and the field remains stationary or vice versa.

When the field is produced by steel permanent magnets the arrangement is known as a "magneto machine," and its usefulness is restricted to machines of small output for special purposes (i.e. for ringing bells, motor ignition, or for generators in testing sets such as the ohmmeters described on page 386).

In all other cases electro-magnets are used to produce the field, and the machine is known as a "dynamo." This term includes both D.C. (direct current) and A.C. (alternating current) generators.

Let us assume we have a magnetic field obtained in any convenient way, and consider a single active conductor in the form of a straight bar moving therein at right angles to the lines of magnetic flux.

It might be moved with a reciprocating action from A to B and back again, the result being an alternating E.M.F. which would change its direction when the direction of motion changed; but as a rotatory motion is much more satisfactory from a mechanical point of view it will be better to attach the bar to the surface of a rotating cylindrical carrier of some kind; and thus we get the arrangement shown on Figure 80.

As before, the result will be an alternating E.M.F. making one complete cycle per revolution, and of "frequency"

equal to the number of revolutions per second. The question of the material of the cylindrical carrier now arises, and the answer really depends largely upon the nature of the field magnets. If they are steel permanent magnets the arrangement will work fairly well even if a wooden or brass carrier be used, because once magnetised their strength is an almost constant quantity which will only be very slightly increased by putting a soft iron carrier between the poles. Soft iron would, however, always be used, but mainly because it concentrates the field in the polar gap.

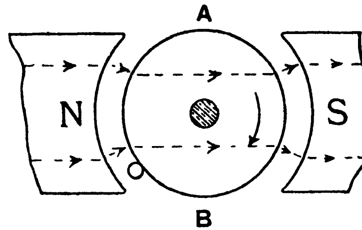


FIG. 80.

With electro-magnets the case is entirely different. Here the field is produced by a magnetising coil, and as its strength for a given number of ampere turns is largely dependent upon the nature of the material in the path of the lines of flux, it is desirable to fill up the polar space as completely as possible with soft iron, leaving only a narrow gap for clearance. If the iron core of the armature of an actual dynamo were suddenly to be replaced by some non-magnetic substance the output of the machine would be reduced to an almost negligible quantity, and to put matters right would require an altogether impossible increase in the number of ampere turns in the field winding.

Yet another difficulty arises, for if the carrier be made of solid iron it will be found to take considerable power to drive it even without any conductors, and it will become very hot. Evidently this is a perfectly natural occurrence due to induced currents in the mass of the iron itself, and involves very wasteful consumption of energy, which can only be avoided by making the iron cylinder a non-conductor in the direction in which these "eddy currents" tend to flow. Hence the armature core must be "laminated," i.e. made up of soft iron rings or discs cut out of sheet metal of the highest magnetic quality and built up side by side until the necessary thickness is obtained. The discs are usually insulated from each other by a thin layer of varnish or paper on one side. Only moderate

insulation is necessary, as the induced E.M.F. in the core is not more than in one active conductor, so that in small machines the natural "scale" on the surface of the stampings may be sufficient.

Having settled the general nature of the core which carries the rotating conductors, we return again to the case shown in Figure 80. If we make connections to the two ends of the bar, while still leaving it free to rotate, we can collect an alternating current from it, the only drawback so far being the weakness of the E.M.F. obtained. The remedy is evidently to use more bars, joining them in series so that their E.M.Fs. are added together. These will all act in the same general way, and we have now to consider how they shall be spaced out upon the core and how they can be connected together to the best advantage.

The first really good solution was to bunch them together in two deep slots in the cylindrical core, as in Figure 81. This is the well-known Siemen's **H** pattern armature, and it is worth noticing both on account of its value in illustrating the principles embodied and the difficulties to be overcome in all machines and also because it still has a distinct sphere of usefulness for small machines of the magneto type. The connection of the conductors in series is effected in the simplest manner, for the winding really amounts to a single coil with two free ends, wound in the grove, and we might have regarded it from that point of view were it not necessary to warn the student at the outset that it is misleading to think of a coil as a unit in an armature winding. Each coil really consists of certain "active conductors" lying on the outer periphery joined together in various ways by other conductors, known as "idle wire," which are necessary evils, since they increase the internal resistance of the armature but take no part in the production of E.M.F. In the present case the portions of the coil crossing the ends of the core consist of idle wire, and obviously the greater the length of the core as compared with its diameter the greater will be the proportion of "active" to "idle" wire. In all cases, however, the relative dimension

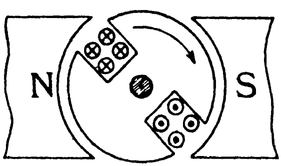


FIG. 81.

are affected by other considerations and are largely a matter of compromise.

By using sufficient turns, i.e. by increasing the number of active conductors, the E.M.F. may be made to have any desired value, and the current may be collected by fixing the two ends of the winding to two "slip rings," i.e. two complete metal rings carried by the shaft but insulated from it and from each other. On these press two brushes, making contact to the external circuit. It is a simple and satisfactory arrangement in itself and would serve for quite large outputs, but the E.M.F. is alternating, and if a direct current is required some form of commutator is necessary. This at once introduces a whole host of troubles and difficulties, although it has the advantage of enabling the machine to excite its own field magnets. In this case the commutator is a ring of metal insulated from the shaft and split into halves by longitudinal slits. To each half one end of the winding is attached, and two brushes rest on them somewhat in the relative positions indicated in Figure 82, which means that the brush connections are reversed at the same time as the E.M.F.

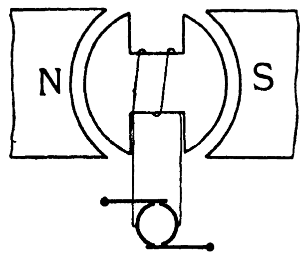


FIG. 82.

If the external circuit be closed the result is a current which externally is continuous in direction, but which falls to zero at every half revolution, and hence is a "pulsating" current and not a steady one.

This fact means that it cannot well be used to charge accumulators, which would discharge back again part of the time in addition to being short-circuited for an instant each half revolution by the brushes. Still more important is the fact that the full E.M.F. of the machine exists as a P.D. across the thin insulation between the two segments of the commutator and is always liable to arc across. This last fact alone completely destroys the utility of the arrangement for large outputs, although, as already remarked, for small machines it is effective and useful.

MAGNETO GENERATORS

The generator such as is used for ringing the magneto bell described on page 36 may here be briefly described.

For such work the utmost simplicity in design is essential; there should be nothing to get out of order, and hence brushes of any kind, if only to collect alternating currents, are objectionable, and some better means must be devised for maintaining connection with the two ends of the rotating coil. A commonly used arrangement is shown in Figures 83 and 84.

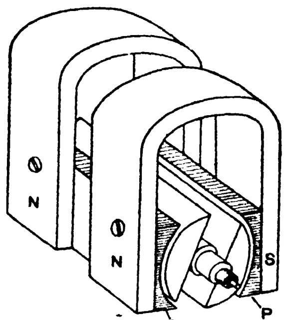


FIG. 83.

The field is supplied by two or more steel permanent magnets NS, screwed to soft iron pole pieces PP, which are bored out to take the armature. As the output is small, and efficiency in its ordinary sense unimportant, this is usually solid and cast in one piece with the shaft, whose bearings are provided by the brass end plates BB, which carry the whole thing, and sufficient speed is obtained by means of a cog-wheel gearing into a larger wheel turned by hand. On the armature is wound a coil of many turns of fine silk-covered wire, one end being secured under a screw R in the shaft, thus making contact with the framework generally, to any convenient part of which one of the terminals T_1 is connected. The other end of the wire must therefore be insulated from the framework, and for this purpose the shaft is bored out at one end, fitted with an ebonite plug I, carrying a metal pin M, whose projecting rounded end makes good contact with an insulated spring strip G, to which is connected the second terminal T. Beyond the bearing a small hole is drilled through the wall of the tube, bushed with ebonite, and fitted with another metal pin M_1 which makes contact with M, and to which is soldered the end of the armature coil. Thus continuous contact of a simple and effective kind is obtained. The machine is also fitted with an automatic device for cutting it out of the circuit except

when actually signalling, but these details have no bearing on the present subject and need not be discussed here.

When magnetos are used for ignition purposes on motor-cars, etc., in order to avoid the trouble of recharging storage cells, the form just described is not very suitable because the E.M.F. will be very low unless the car is running at a good speed, and in any case cannot easily be made high enough to

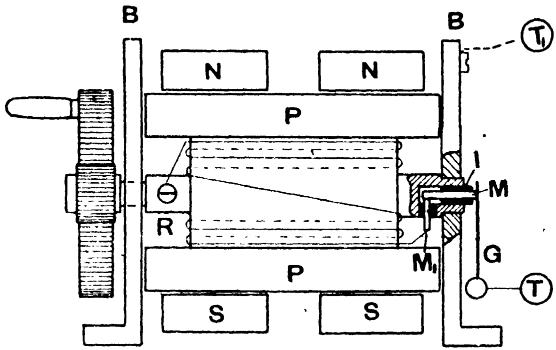


FIG. 84.

produce a suitable spark.[1] Hence the design is considerably modified, and in what is called the high-tension system the arrangement is really a combination of generator and induction coil.

Another plan, based upon the facts stated on page 102, is known as low-tension ignition. In this case self-induction is introduced into the magneto circuit, and the spark obtained by suddenly breaking the circuit inside the gas chamber.

ARMATURE WINDINGS IN GENERAL

Modern types of armature windings are best approached by noticing that if we wish to use as many active conductors as the space permits, the best way will be to space them uniformly all round the core one or more layers in depth. These are the

[1] See Appendix IV, p. 189, for a description of modern ignition magnetos.

real units in our winding, and will all be exactly equivalent; we thus get the distribution shown in Figure 85.

The active conductors may at any instant be divided into two groups, those moving upwards through the field, and those moving downwards through it, and for every conductor in each group the direction of the induced E.M.F. is the same, although its magnitude varies with the position in the manner roughly indicated by the thickness of the crosses or dots. The key diagram gives the actual direction in each group, and, as before, the question arises, how are they to be connected together? Without discussing all possible or obsolete types, the principle of two general methods should be understood, these being known as the "ring" and "drum" winding respectively.

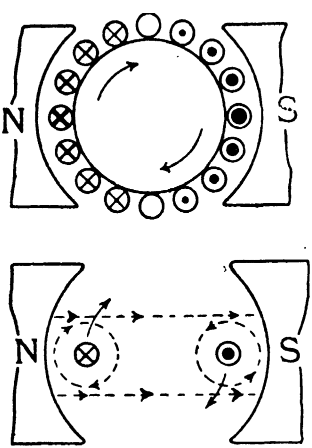


FIG. 85.

The latter is almost exclusively used in practice, but the former is easier to understand, and therefore we will deal with it first.

It was devised by Pacinotti, and developed into a practical form by Gramme. In this case the armature core is a hollow laminated cylinder or ring, and consecutive active conductors are joined together by connections passing through its interior, as shown in Figure 86.

When this is carried out all round the ring it is equivalent to a simple closed winding as shown, and a comparison of Figures 85 and 86 will show that all the conductors whose E.M.Fs. are in the same direction are in series, two similar groups being formed whose total E.M.Fs. are equal and opposite, so that no current can flow as yet. The connections inside the ring and round its edges must be regarded as merely contrivances for joining the active conductors in series, i.e. as "idle wire." It will be evident on inspection that if the inner conductors were also to cut the magnetic lines the E.M.F. set up in them would be in the wrong direction, and hence the

lines of the field must not penetrate the interior of the ring, but must be confined to the iron core as shown in Figure 86, so that only the outer conductors are rotating in a magnetic field.

If now two brushes, connected to the external circuit, be supposed to rub on the conductors between the pole tips, the two halves of the winding become joined up in parallel to that circuit and both E.M.Fs. unite in maintaining a current therein. The arrangement is equivalent to two voltaic cells connected in parallel, and the actual E.M.F. obtained between the brushes will be that due to half the active conductors in series, whilst the current will be, externally, twice that flowing in any one conductor.

It will also be evident that the E.M.F. and therefore current will be almost uniform, as the number of conductors in series producing that E.M.F. is practically constant.

It would be obviously inconvenient to make the collecting brushes press directly upon the bare surface of the active conductor (although this has been done in certain obsolete types), and it is easy to obtain exactly the same result by connecting them to a number of insulated copper bars which constitute the commutator and from which the current is collected by the brushes. The simplest arrangement theoretically, and it will be found later also the best practically, would be to have one commutator bar to each active conductor as at A in Figure 87. This would mean in most cases an impossibly large number of bars, and their number may be reduced by winding the armature in "sections" containing more than one active

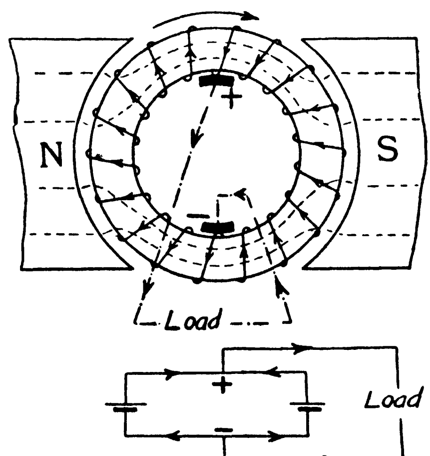


FIG. 86.

conductor. For instance, the winding (B) shown in Figure 87 has three active conductors in each section, and the number of bars will be only one-third of the number of active conductors. This grouping does not appreciably affect the E.M.F. or the output, and as far as we have gone at present there appears to be no objection to it. The matter cannot be profitably discussed at present, but a few general remarks may be useful.

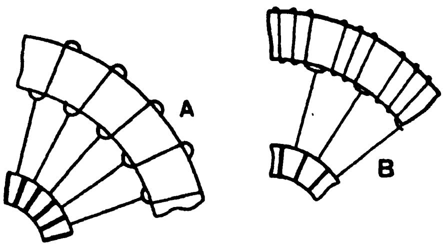


FIG. 87.

In the first place it will be noticed that although the E.M.F. induced in any one conductor varies with its position, yet the current through it is necessarily the same for all positions right up to the brush. Here, whatever its magnitude, that current must stop, start again, and reach the same value in the opposite direction in the very brief time the conductor takes to pass the brush; and from what has been already said (see page 108), it is evident that this is an operation equivalent to a periodic reversal of the motion of a flywheel. In any case it is an operation naturally requiring a certain small but definite amount of time, which increases with the mass of the wheel. When the winding is grouped in sections as above the current must be reversed in a whole section at the same instant, and it corresponds to a heavier wheel. Hence, whatever be the real nature of the reversal process, it will take place more readily the fewer the number of conductors in each section. Any failure to secure satisfactory reversal shows itself in the form of sparking at the brushes, which is most injurious to the commutator and not permissible in modern machines.

Another mechanical analogy may be helpful. Represent one-half of the winding by a train in motion of constant total mass. Each section then corresponds to one carriage. When there is only one conductor in each section, the carriages are numerous and light; when there are many conductors in each section, the carriages are few and heavy. The other half of the winding will then be represented by an exactly similar

train moving in the opposite direction. Not to confuse matters, ignore the locomotives, and consider each carriage as self-driven : let these two trains be moving side by side in opposite directions, but never passing each other, because at each instant and at both ends a carriage is detached from one train and attached to the other, so that each carriage in turn has suddenly to stop and to start again in the opposite direction.

Obviously it is a delicate operation at the best to carry out without shock or jar ; the actual details need not be considered, but it is also evident that the lighter and more numerous the individual carriages are the less trouble will be met with in consequence of their inertia. Hence the practical advantage of keeping down the number of conductors per section and of using many commutator bars. Such a construction carries with it, however, increased size and cost for a given output, and, as frequently stated, the actual arrangement adopted must be a matter of compromise.

A fuller consideration of the question of commutation is given in Appendix I to this chapter.

We may next consider the action of a ring-wound armature when placed in a four-pole field.

This case is shown in Figure 88, and we notice that although the ring is wound in precisely the same way as before there are now four opposing E.M.Fs., and in consequence four brushes are required, the two positive and the two negative brushes being connected together. The diagram also shows that the current in any one armature conductor is now only one-fourth of the current in the external circuit, so that if we imagine the latter to be 1000 amperes, each conductor would carry 250 amperes, whereas if the same current were taken from a two-pole machine, each conductor would have to carry 500 amperes. Similarly a six-pole field would mean six brushes, and the current per conductor $\frac{1000}{6}=166{\cdot}6$ amperes, and so on for any number of pairs of poles. In such cases all the brushes of one sign are often fixed to a separate circular carrier to facilitate their cross-connections. It would be quite possible, instead of cross-connecting the brushes, to connect together permanently those armature conductors which are always at the same potential ; for instance, with a four-pole field this would mean joining each commutator bar to the one

diametrically opposite, and with a six-pole field to those a third of the way round, and so on; then only two brushes would be absolutely necessary whatever the number of poles, although more might be used if desired. These brushes would be 90° apart for a four-pole field, and either 60° or 180° for a six-pole field. Although this plan simplifies the brush system, it is radically bad in itself for large outputs, because all the current must be collected at two brush sets, and it is very much better to use a larger number and subdivide the output between them, apart from the fact that such a cobweb of cross-connections is expensive and difficult to carry out satisfactorily.

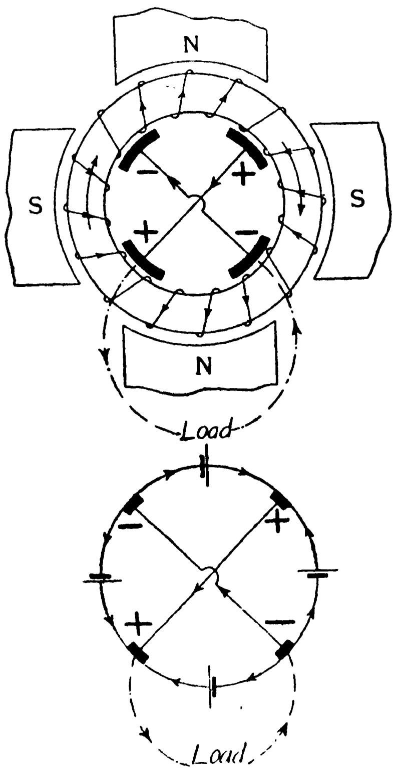


FIG. 88.

It is needless to discuss here the many details and variations in this form of winding, for, in spite of certain conspicuous merits, it is now almost entirely superseded by the "drum" method of grouping the active conductors. Of its advantages the most important are (1) easiness of insulation, the P.D. between two adjacent conductors being always small, so that high electro-motive forces can be readily obtained; (2) the same winding will answer, no matter how many poles are used for the field. On the other hand, (1) it is necessary to support the discs on the shaft by non-magnetic material, without cutting away much iron from them or taking up room required

for the inner conductors; (2) it is always difficult to get as much cross-section of iron into the core as desirable; (3) more than half the winding necessarily consists of idle wire. The one great drawback, however, to which the others are merely trifles, is the fact that the sections cannot be wound and insulated separately and then slipped into place on the core. The armature must be slowly wound by hand, the services of a skilled winder being required for the whole of the job.

DRUM WINDINGS

These are rather more difficult to follow, but can be deduced from the ring winding as follows:—

For this purpose it is convenient to take the case of a four-pole field. Figure 89 shows a ring-wound armature having

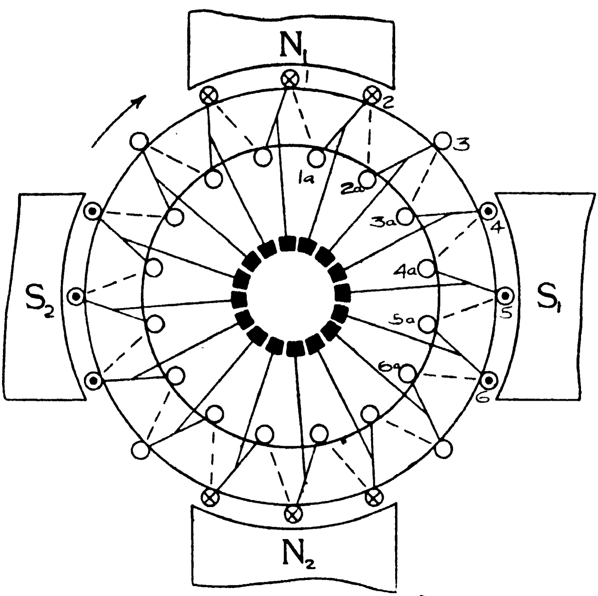


FIG. 89.

sixteen active conductors and one commutator bar per conductor in such a field. Inside the ring are other sixteen conductors, which, with the end connections, serve to join the

active conductors in series and in which no E.M.F. (unless perhaps a counter E.M.F.) is induced. The problem before us is to devise a means of making these inner conductors 1*a*, 2*a*, 3*a*, etc., useful for producing E.M.F.[1]

Obviously this can only be done by placing them on the outer periphery of the armature core.

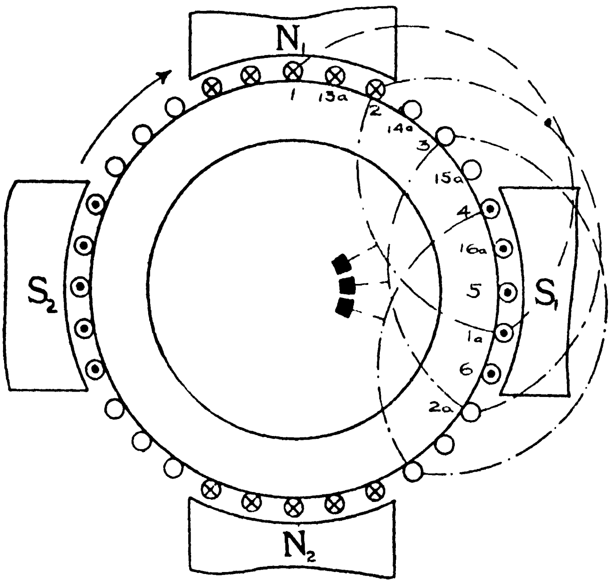


FIG. 90.

Let us consider in detail the conductors 1 and 1*a*. Where shall 1*a* be placed in order to satisfy two conditions: (1) that it shall be active, (2) that its E.M.F. shall be in the right direction, i.e. in series with that of 1, it being understood that in this operation we are not in any way altering the existing connections? An inspection of the figure will show that if 1 is under a N pole, 1*a* must be under a S pole (either S_1 or S_2 would do; assume S_1 is used). As regards its exact position,

[1] For this method of showing the relationship between drum and ring windings we are indebted to Professor Cramp.

it will be desirable to place it as nearly as possible in the same position relative to S_1 as 1 is to N_1, i.e. about one-quarter of a circumference ahead, which will bring it between 4 and 5, or 5 and 6. Let it be placed between 5 and 6. Reasoning in the same way we see that the conductor *2a* must be placed between 6 and 7, and if we continue this process until there

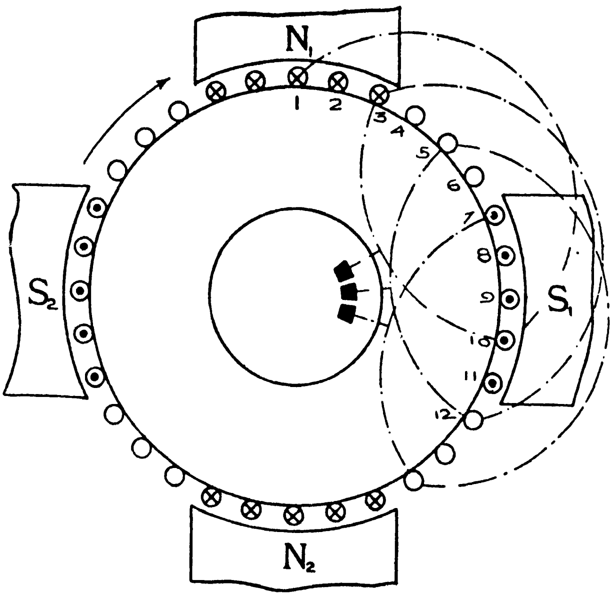


FIG. 91.

are no conductors left inside the ring, we arrive at the ordinary drum winding as shown in Figure 90.

But notice that whereas *1a*, *2a*, etc., whilst in their original position within the ring were at nearly the same potential as the adjacent conductors, they are now brought into contiguity with conductors which may be at a very different potential, and therefore extra insulation will be necessary between them.

As we have not altered the connections, the new winding will have the same number of commutator bars and brushes

as the corresponding ring, but will give twice the E.M.F. in the same field and at the same speed. Of course conductors must be smaller or else the armature larger in order to find room for them. Further, as each active conductor on the ring gives rise to two on the drum, the total number in the latter case must always be even. These may be arranged in sections, as already explained, but in the ring each section contains one group of active conductors, whilst in the drum it contains two such groups. Hence, other things being the same, the latter winding requires only half the number of commutator bars.

We have derived the drum winding from the ring merely to bring out clearly the principles involved, and it will now be more useful to formulate some simple rules for joining up the conductors in any given case.

Figure 91 is precisely the same as Figure 90, except that now the conductors are numbered consecutively, 1*a* becoming 10, 2*a* becoming 12, and so on. The interval between 1 and 10 (or 1 and 1*a*) is known as the *forward pitch*, and that between 10 and 3 (or 1*a* and 2) is known as the *backward pitch*. This is two less than the forward pitch. Let these be p_1 and p_2 respectively. Then p_1 must always be roughly equal (preferably slightly greater) to the distance from the centre of one pole to the centre of the next (a distance known as the *pole pitch*), and must also be an odd number. For if it be an even number a little thought will show that the winding would not include any of the conductors with even numbers. Hence we can define p_1 as being the nearest odd number to $\frac{C}{P}$ where C is the total number of active conductors, and P is the number of poles. For instance, in this case we have C=32 and P=4, and therefore $\frac{C}{P} = 8$, so that the forward pitch may be either 7 or 9, preferably the latter, whilst the backward pitch is either 5 or 7.

Figure 91 shows the latter case, and the arrangement may be summarised in the form of a " winding table " :—

In this C stands for commutator, and F and B for the front and back respectively. It means that starting from commutator bar 1 we go down by conductor 1 from front to back,

returning from back to front by conductor 10, and then connecting to commutator bar 2. From this we go down by conductor 3 and return by conductor 12, then connecting to bar 3, and so on, until the winding closes by a return to bar 1. It will be seen that the rule is to go down by odd numbers and to return by even numbers (if we begin with an odd number, or vice versa if we begin with an even number).

C	F	B	C
1	1	10	2
2	3	12	3
3	5	14	4
4	7	16	5
5	9	18	6
6	11	20	7
7	13	22	8
8	15	24	9
9	17	26	10
10	19	28	11
11	21	30	12
12	23	32	13
13	25	2	14
14	27	4	15
15	29	6	16
16	31	8	1

This scheme of connecting gives what is known as a *lap winding*, and as it is analogous in all respects to the ring winding from which it was derived, it follows that there will be as many complete paths through the armature winding as there are poles, and the remarks already made as to the multipolar ring will hold good without alteration.

It must be understood that this is by no means the only method, or even the most generally used method, of connecting up the conductors; it is merely the simplest to begin with. For instance, it is possible to join the conductors so that there are only two paths through the armature, one-half of the total number being in series no matter how many poles are used. This is known as a two-circuit or wave winding. Its consideration, and that of many important practical details of drum windings, cannot be now undertaken; here only the briefest outline has been attempted. We may note in conclusion that a drum armature wound suitably for a field having any definite number of poles will not work in a field having any other number, unless alterations are made in the winding, whereas a ring armature works equally well in any field irrespective of the number of poles, assuming it to be provided with the appropriate number of brush sets.

E.M.F. PRODUCED IN ARMATURE

For a given number of active conductors in series this will be the same in the same field and at the same speed for either the drum or ring winding and can be easily calculated as follows:—

Considering a two-pole field, let Φ magnetic lines actually

pass through the armature, which has C active conductors counted all round the core, and makes n revolutions per second.

Now from the definition already given we know that when one conductor cuts one line per second, one unit of E.M.F. is produced, and in this case each conductor cuts $2 \times \Phi$ lines per revolution, and therefore $2\Phi \times n$ lines per second, so that the average E.M.F. per conductor is $2 \times \Phi \times n$ absolute units.

Again, $\frac{C}{2}$ conductors are in series, so that the actual average E.M.F. is $2 \times \Phi \times n \times \frac{C}{2}$, which must be divided by 10^8 to express it in volts. In the case of a four-pole ring winding, or a drum winding of the kind just explained, it will be found that one-fourth of the active conductors are in series, and if we now let Φ stand for the number of lines emerging from each pole face the expression becomes :—

$$\text{E (average volts)} = \frac{4\Phi \times \frac{C}{4} \times n}{10^8}$$

Thus far the coefficients cancel out ; but there are forms of multipolar windings in which this is not the case, and the best way is to write the formula in words as follows :—

$$\text{E (average volts)} = \frac{\text{number of lines cut per conductor per revolution} \times \text{number of conductors in series} \times \text{revolutions per second}}{10^8}$$

This is true for any form of winding.

Having settled the number of active conductors in a given case, their area of cross-section is determined by the maximum current to be carried and the permissible rise of temperature. As a rule the ventilating and radiating conditions in a rotating armature are such as to make it possible to work at a higher current density than would be desirable or safe for a stationary coil, something like 3000 amperes per square inch being a very common practice. It must also be remembered that the current carried by any one armature conductor is never more than half the current in the external circuit, and with four poles and upwards it may be less still.

SLOTTED VERSUS SMOOTH ARMATURE CORES

Considerable diversity of opinion and practice has existed in the past on this point, but at the present time the slotted core is in practically universal use.

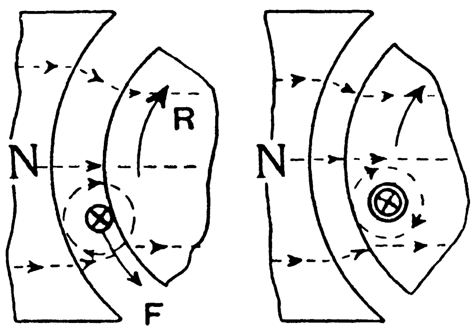
It is well worth trying to realise clearly the nature of the problem on account of the insight it gives into fundamental principles. First, it must be remembered that the resistance to motion met with in driving a dynamo, and the turning effort developed in a motor, are both due to the force on conductors carrying a current in a magnetic field, and that this force has in some way to be transmitted from the conductors to the shaft.

It is as if an armature at work as a generator were rotating in a friction clutch which tended to stop the active conductors and to make them slip backwards, and as if an armature working as a motor were driven round by the push on the conductors, the load meanwhile tending to stop the rotation of the shaft. This *magnetic drag*, as it is termed, must be allowed for in the case of a smooth core by providing metal projections let into the core at intervals for the conductors to push against, and it evidently increases the difficulty of securing adequate mechanical strength, whereas when the conductors are imbedded in slots an excellent "drive" is obtained. This, important as it seems, is in itself by no means sufficient, and it can be safely said that if the slot construction merely gave a better drive, modern developments in heavy electric traction, etc., would have been almost impossible, or, at all events, progress would have been very much retarded. The cause of the difficulty lies in the fact that the copper conductors must be separated from the iron of the core by insulating materials, and there are no good insulators which are mechanically strong. Whenever a stress exists on the conductors, it must be taken up by the insulation and transmitted to the core, or vice versa, and it is evident that even conductors imbedded in slots would be continually tending to squeeze out the insulation on the driven side, an action which must inevitably shorten the life of the armature.

All this is strictly true for smooth core armatures, but both experiment and theory show that conductors in slots do not feel the stress to anything like the full extent, and in fact

when completely surrounded by iron (by being passed through holes in the core discs) do not feel it at all, and have no tendency whatever to squeeze out the insulation. Narrow deep slots, however, give sufficient relief from stress for most practical purposes, and have such other advantages that the more expensive construction is seldom used.

It is not that the stress does not exist ; it is essential to the performance of work, but it now comes mainly upon the iron core, which can easily stand it. Much unnecessary difficulty has been created in trying to explain this interesting and important fact, mainly through not noticing that although



R. Direction of rotation. F. Direction of force.

(*a*) FIG. 92. (*b*)

it is convenient to speak of a conductor as being acted upon by a force when carrying current in a magnetic field, yet really, as already shown, the force is between two magnetic fields, one of them due to the current itself.

Figure 92 shows the state of affairs.

In (*a*) it is evident that the stress between the two sets of lines of magnetic flux must tend to drive the conductor backwards, whereas in (*b*) the field around the conductor will be mainly in the iron, and will resist being driven out of the iron, and as long as this is the case the stress will be wholly on the iron and not on the conductor. If it be objected that these diagrams are not correct pictures of the actual resultant field it may be answered that they represent its components in such a way as to serve their purpose, and no good end would be

attained by going more deeply into matters at this stage of progress.

Notice that the induced E.M.F. is in no wise altered. The conductors cannot possibly escape cutting the field however they may be imbedded in iron.

The universal popularity of slotted armatures follows from these considerations, but in some respects they are inferior to those having smooth cores, chiefly from the point of view of satisfactory commutation, and there is always a certain amount of eddy current loss in the pole-pieces due to the flickering of the lines from tooth to tooth, which is altogether absent from the latter type. Another point of some importance is the difference in the length of the air-gap between iron core and pole-piece. Here the advantage to some extent lies with the slotted cores, and the immediate result is a reduction in the ampere-turns required for the field, but the length of the air-gap is influenced by other considerations, and the matter must be left to be dealt with later.

THE FIELD-MAGNET SYSTEM

The function of the field magnets is to provide a magnetic field in which the armature can rotate, and the ideal place for the field winding would be over the armature itself, as shown in Figure 93; but as sufficient room is not available there, it must be placed elsewhere. Generally speaking, that design is best which in the simplest and most direct way conveys the field to the armature. Hence the many and sometimes fantastic forms figured in old text-books have gradually given place to a few simple types in which the chief considerations are mechanical strength, shielding of the windings from accidental injury, and the shortness of the magnetic circuit.

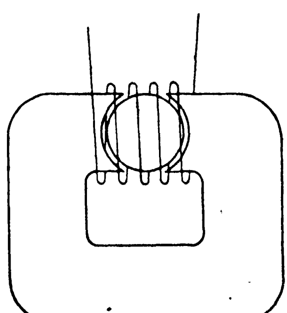


FIG. 93.

The actual shape and dimensions of the field magnets must depend largely upon the magnetic character of the iron which

is to be used. At first the only materials were cast and wrought iron, but for some time mild cast steel has been available, and is now very largely used. This is really a kind of soft iron, the name being derived more from the method of manufacture than from its properties, and it has the advantages of being readily cast and easy to tool combined with high magnetic quality. It may be regarded as iron containing just enough carbon to make it sufficiently fusible. Wrought iron is the purest commercial form of iron, very good magnetically, but as it cannot be cast on account of its very high temperature of fusion the expense of forging is almost prohibitive except in simple shapes. Ordinary cast iron is magnetically poor, and field magnets made entirely of it must be much larger and heavier on that account, also the cost of copper will be greater because the length of each turn is greater. At the same time it is still useful for certain purposes.

The magnetic properties of iron are usually expressed in the form of a magnetisation curve which gives the relation between the "magnetising force" applied to the iron, a quantity denoted by H, and the flux density thereby produced in it, denoted by B.

For a magnetising coil and core of fixed dimensions the former depends only upon the ampere-turns, and is quite independent of the nature of the core. The student should regard it as a cause which produces a certain effect, which we call a magnetic field, in the surrounding medium. This medium may be of air or other non-magnetic material, or wholly of iron, or partly of iron and partly of air, etc., the main point being that the same "magnetising force" may produce very different magnetic fields according to the nature of this medium. The strength of this field inside the coil is conveniently expressed in terms of the number of lines of magnetic flux per square centimetre of cross-section, and this quantity is termed the flux density produced in the core. A given magnetising force will produce a certain flux density in air, a much greater one in iron, and this again will be more or less according to the magnetic quality of the iron. (See Appendix II to this chapter.)

Figure 94 gives typical magnetisation curves for cast iron, wrought iron, mild cast steel, and charcoal iron stampings such as are used for transformer and armature cores. The

general nature of such curves is always the same, although they may differ considerably among themselves. When a very small magnetising force is applied to the iron and gradually increased, there is a short initial stage, not perceptible in the diagram, during which the magnetisation produced rises rather slowly, then a stage is reached during which a very slight increase in the magnetising force produces a very great

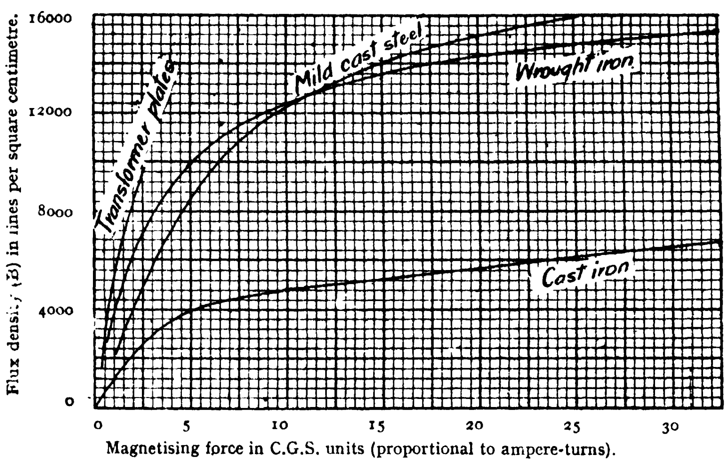


FIG. 94.

increase in the magnetisation, the curve rising steeply until it more or less suddenly bends over, showing that the iron is becoming "saturated." Beyond this stage further increases in H (i.e. in the ampere-turns) only produce relatively slight increases in B.

It will be seen that cast iron cannot be magnetised to anything like the extent of either wrought iron or mild steel. These latter are both good, the former being better at low flux densities and the latter at high flux densities, but as field magnets will be usually worked at a stage not much below and sometimes slightly above saturation, the advantage really lies with the steel. It would be different in the case of transformer stampings. These must always work at a much lower flux density (to avoid losses in the iron which do not

occur with direct currents), and therefore the lower part of the curve is the more important. In the case given this is not taken beyond $B=10,000$ lines per square centimetre, but it shows the very high magnetic quality at low flux densities of the specimen selected for illustration.

Evidently some way of numerically expressing the idea of magnetic quality is required. This is conveniently measured at any part of the curve by the ratio $\frac{B}{H}$, because the greater the value of B for a given value of H, the better is the magnetic quality of the iron. The numerical value of this ratio is termed the **permeability** of the iron, and is always denoted by μ. In the ordinary electrical units the permeability of air is taken as unity, and if the value for iron in a certain case works out to (say) 2000, it means that a given number of ampere turns applied in a suitable way would produce 2000 times more lines per square centimetre of cross-section in the iron than they would in air.

If we find from the magnetisation curve the value of the ratio $\frac{B}{H}$ at different points upon it, we can plot a new curve giving the relation between permeability and flux density. This has been done in Figure 95 for the curves given in Figure 94, and it shows that in each case the permeability is low during the initial stages of magnetisation, but increases fairly rapidly until it passes through a maximum, when B is something like 5000 to 7000 lines per square centimetre, then decreasing until it becomes very small at and beyond "saturation."

It also shows the great difference in permeability for the different materials, and the superiority of cast steel to wrought iron at high flux densities.

In designing the iron part of any machine, the greater the value of B is taken, the smaller becomes the cross-section and weight of iron to be used; but, on the other hand (except for low flux densities), the greater becomes the relative number of ampere-turns required in consequence of the fall in permeability. In practice, field-magnet cores of cast steel would be worked at about 14,000 to 15,000 lines per square centimetre.

Drum armature cores made of stampings, whose quality is indicated sufficiently well at present by the curves for transformer iron, may have B=10,000 below the teeth and twice as much in the teeth themselves.

In transformer cores B will often be as low as 5000, and will seldom exceed 8000 lines per square centimetre.

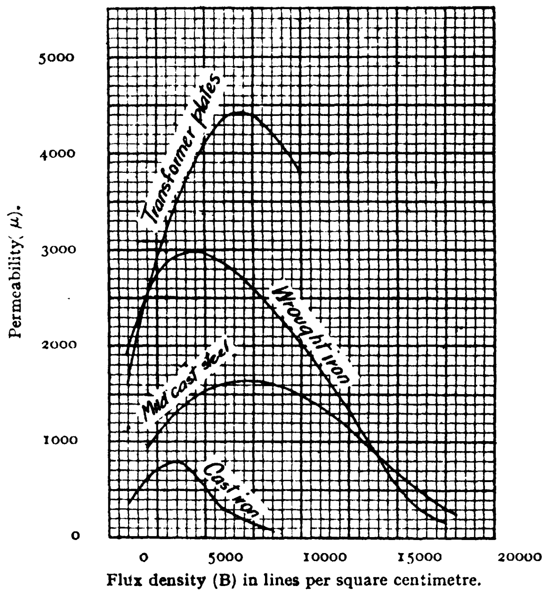


FIG. 95.

It must be remembered that no two samples of iron are quite alike in their magnetic properties, and that such curves as those given above cannot be applied indiscriminately. In practice values must be obtained for the actual iron to be used, unless merely approximate accuracy is sufficient.

THE FIELD WINDING

From what has been said it will be evident that the effect of this winding depends upon the ampere-turns, and the number required in any given case may be calculated from

the dimensions of the various parts, provided the magnetisation curves are available. Assuming this quantity determined, it may be obtained in various ways.

Series Winding

This is the oldest method, and is shown diagrammatically in Figure 96.

In this case the whole current given out by the machine is passed through the field coils, which are therefore of adequate cross-section, but need not consist of many turns. Their resistance is kept very low, usually less than that of the armature, to avoid I^2R loss. This winding is inexpensive, and quite satisfactory when the current output is to be constant (for then the ampere-turns are constant), but as that is very seldom the case it is but little used for generators. The only important application is in constant current machines for series working and these are rarely used. Generators are mostly required to give constant E.M.F. with a varying current, and this, from the form of the E.M.F. equation already given, evidently means a field of constant strength, whereas it is obvious that with a series winding the strength of the field will vary when the current varies. On open circuit there will be no field and no E.M.F. except the small amount due to residual magnetism, and on closed circuit we might expect the E.M.F. to increase steadily as the current, and therefore the field, increases. To a certain extent this is true. The actual behaviour of a given machine at various loads is conveniently expressed in the form of a **characteristic curve,** giving the relation between the P.D. at terminals and the current.

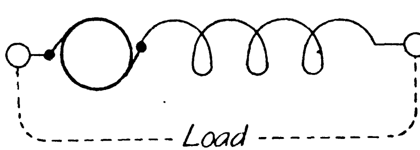


FIG. 96.

Such a curve for a series wound field is given in Figure 97. It must be remembered that the P.D. at terminals, i.e. the volts actually measurable, is not identical with the E.M.F. induced in the armature as given by the E.M.F. equation, but will be less than that quantity by an amount depending upon the current and the internal resistance of the machine. If I be the current, R the internal resistance, E the induced

E.M.F., and V the P.D. at terminals, then IR volts will be lost through internal resistance and $V = E - IR$. Now if we suppose the circuit to be closed through a high resistance which is gradually decreased, the induced E.M.F. E will rise as the field increases, its behaviour being shown in Figure 97. But the P.D. at the terminals will be less than E by an amount

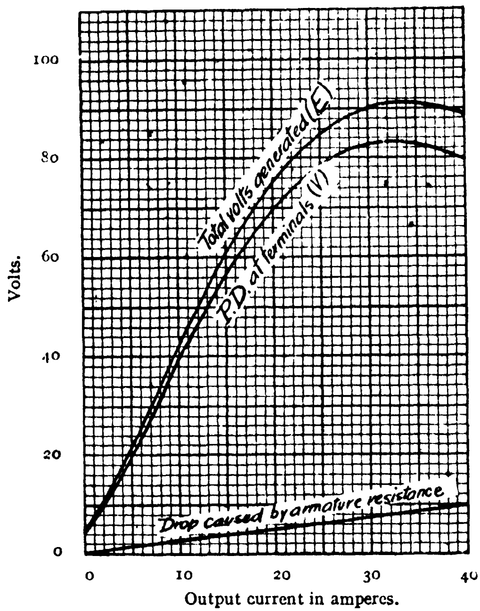


FIG. 97.

that steadily increases with the current, and hence beyond a certain output its value will begin to decrease. There are also other reasons which cannot be dealt with here which tend to cause such a decrease, and the result is as shown. There is no considerable range of output with approximately constant E.M.F., and hence such a machine is unsuitable for lighting a variable number of lamps in parallel, or for any work in which the current is liable to vary to any great extent.

Shunt Winding

In this case the necessary ampere-turns are obtained by diverting a small part of the armature current through the field winding (as in Figure 98), which therefore consists of many turns of fine wire, and has a much higher resistance than that of the armature. The great advantage is that the field is now of nearly constant strength, because a change in the current output does not directly affect the exciting current in the shunt winding. This latter current depends only upon the P.D. between the terminals of the shunt coil, and would be quite constant if that did not alter.

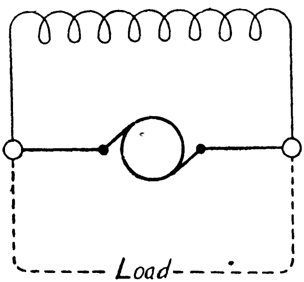


FIG. 98.

But as already explained, even if the armature E.M.F. remained absolutely constant, the P.D. between the brushes would certainly drop as the current increased on account of the volts lost through internal resistance.

The smaller the resistance of the armature the smaller this drop will be, but it will always exist ; hence apart from other

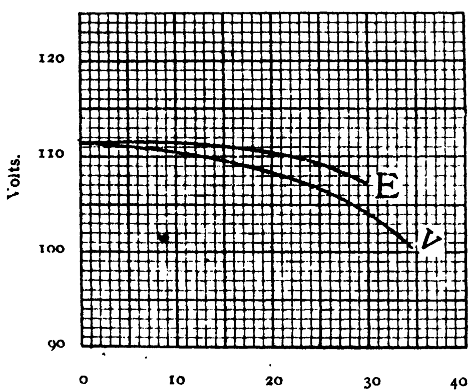


FIG. 99.

reasons the P.D. between the terminals must fall somewhat as the load increases. This will slightly reduce the shunt current and thereby weaken the field, but the effect will be small if the field magnets are fairly well saturated. It therefore appears that the properties of a shunt winding are—(1) the machine can excite itself when the external circuit is open; (2) the P.D. between the terminals will then have its maximum value and be practically identical with the induced armature E.M.F.; (3) this P.D. will slightly but steadily drop as the output increases.

The characteristic curve of such a machine for the working range of current will be of the form shown in Figure 99.

The voltage is much more uniform, but there is still a drop, and evidently the only way to avoid it is to increase the induced E.M.F. by the necessary amount. For instance, to take a rough example, let the armature resistance be 0·2 ohm and the armature E.M.F. 220 volts. Then (neglecting other actions which would still further lower the voltage) on open circuit the P.D. between terminals will be 220 volts, and with a current of 40 amperes it will be $220-(40\times0{\cdot}2)=212$ volts, and so on. If, however, the armature E.M.F. can be increased by 8 volts when the current is 40 amperes, the voltage remains 220 volts as at first. This increase may be obtained either by increasing the speed or the field strength, the latter plan being obviously much more convenient. Two methods of increasing the field strength are available.

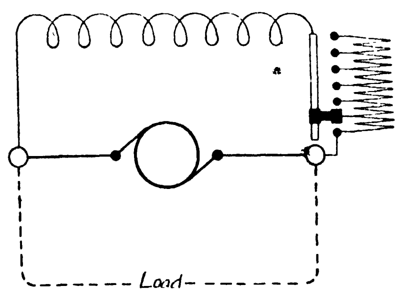


FIG. 100

The first is to put an adjustable resistance in the shunt circuit, by means of which the field current can be regulated within certain limits, and hence the voltage raised or lowered as required. The method is good, and very generally used, the only drawback being that it is not automatic. For some purposes, especially in central station work, this is

unimportant. When it is important the second method of regulation may be used, the result being what is known as a "compound wound" machine.

Compound Winding

The field magnets are in this case provided with two independent windings, one of which is the shunt winding just described, and the other is an additional series winding which need not consist of a large number of turns, but which must be thick enough to carry the full load current of the machine (Figure 101).

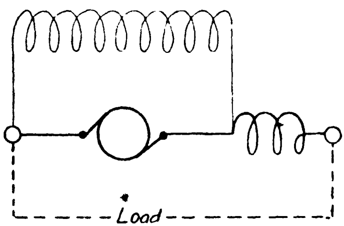


Fig. 101.

It may be connected up in various ways, all of which amount to much the same thing, the exact arrangement being merely a question of convenience.

The series winding evidently produces a magnetising force whose ampere-turns are proportional to the load, and which may therefore be made to automatically compensate for all causes of "drop" by increasing the field strength, and therefore the induced E.M.F. to the required extent, or it may

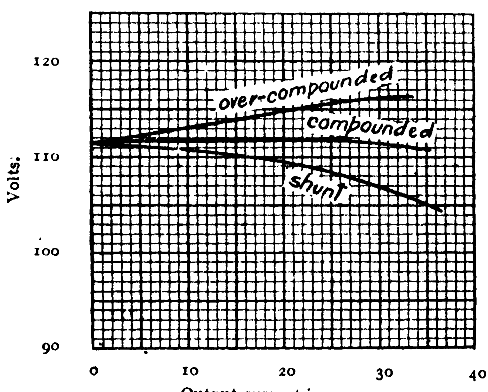


Fig. 102.

be arranged to make the P.D. at terminals rise as the load increases. In such cases the machine is said to be "over-compounded."

The characteristic curve in the former case would be a straight line parallel to the axis of current; in the latter it would rise as current increased. Of course actual curves are not exactly straight lines, but may be very fair approximations thereto.

SELF-EXCITING PRINCIPLE

So far nothing has been said as to the manner in which the field magnets become excited.

This depends entirely upon their being slightly magnetised to begin with. If the iron be perfectly free from magnetism the machine will not excite, although in practice iron usually acquires some slight polarity from the earth's field, or in other ways which is often sufficient to start the action. Otherwise a current from a battery or another dynamo may be passed momentarily through the windings. Assuming the field coils are correctly connected up to the armature, the direction of this initial polarity is immaterial, except in so far as it determines the direction of the E.M.F. produced.

When the armature rotates in this very weak initial field, a slight E.M.F. is generated, and if the circuit be complete a small current flows through the field coils in a direction which tends to strengthen the field. If by mistake the coils are wrongly connected, the current flows in a direction which tends to weaken it, and then the machine will not excite unless either its direction of rotation be reversed or the field connections interchanged. If all is correct a somewhat stronger field is produced, and consequently a somewhat stronger E.M.F. is induced, which in its turn produces a stronger current, and this again a stronger field. Thus the machine rapidly "builds up." On the face of it this reasoning suggests a continuous process, in which both strength of field and induced E.M.F. increase without limit. Practically as the iron approaches saturation the effect of a given increase in field current becomes rapidly less, and a steady state is reached, for which the E.M.F. and field have definite values unless some alteration is made in the working conditions. When the machine stops the field almost completely disappears, but the

" residual magnetism " is sufficient to cause it to " build up " when again started. If the polarity of the field magnets becomes reversed in any way, it does not affect this action, but merely reverses the direction of the induced E.M.F., a quite

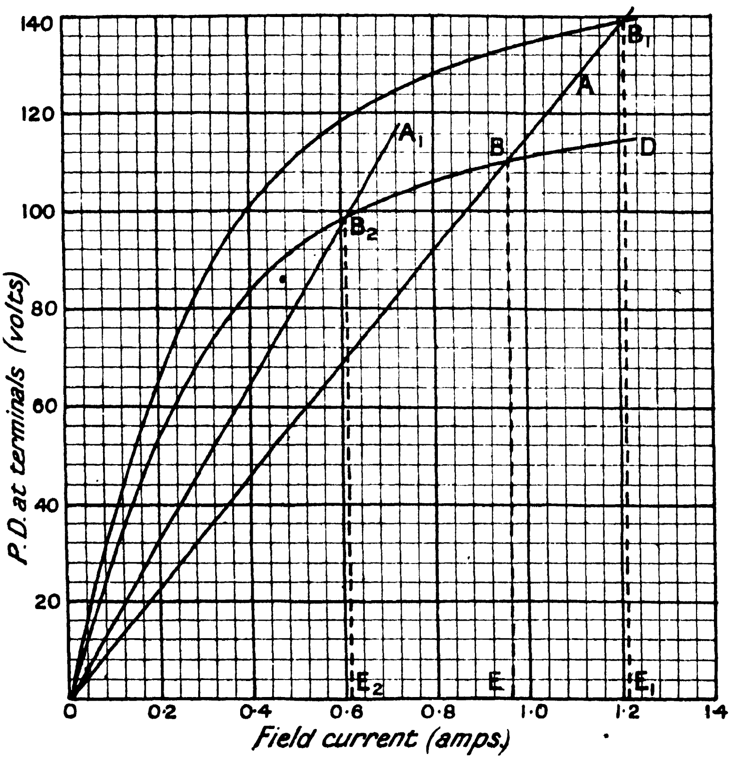


FIG. 103.

unimportant matter unless accumulators are to be charged, or lamps to be run, which, like Cooper Hewitt or Nernst lamps, require a definite direction of current.

Problems of self-excitation are most commonly met with in connection with shunt excited machines and the matter may be looked into more precisely by considering Figure 103.

On account of the peculiar connection of the field coils to the armature in this type of machine, we have the P.D. of the armature applied to the field coils through which a current is sent whose magnitude is settled by Ohm's Law. This field current results in an appropriate strength of field which develops in the armature an E.M.F. and this E.M.F., in turn, subject to a small deduction due to armature resistance, is the P.D. which is applied to the field coil. For any fixed conditions of working the several quantities involved in this operation must take up such values as will result in stability. In the Figure the graph OBA represents the current sent through the resistance of the field coil by various values of applied P.D., while the graph OBD represents the P.D. resulting from the rotation of the armature in fields produced by various values of field current (this graph is called the magnetisation curve of the machine). In general, these graphs will cross as at B, and the ordinate EB represents the value of the P.D. at the terminals to which the machine will build up. For the running conditions specified, the point B is the only point for which the P.D. sends such a current through the field coils (in virtue of Ohm's Law) as will, in turn, give (by dynamo action) the same value of P.D. at the terminals of the machine. This P.D., owing to the shunt connection of the field coils, also, of course, being applied to the field system. If the speed of the machine is increased, the Ohm's Law graph is not affected, but the ordinates of the magnetisation graph will be increased in the same proportion as the speed has been increased, and we now find that the point of intersection of the graphs is at B_1, giving a new, and higher, value for the P.D. (E_1 B_1) at the terminals to which the machine will build up under the new conditions. Again, if we run the machine at the original speed but insert additional resistance in the field circuit, the magnetisation graph will not be affected, but the Ohm's Law graph will take up the new position OB_2A_1 and the machine will now excite so as to give a P.D. at the terminals represented by E_2 B_2. It will be seen that if we put too much resistance in the field circuit, or if we run the machine at too low a speed, the two graphs will not intersect and in such cases the machine will fail to excite. There are, of course, many possible causes of failure to excite, due to reasons which prevent the proper sequence of operations which have been

outlined, and the most important of these are listed below. The location of the precise cause of failure to excite in any specific case is an interesting problem, but lack of space prevents its discussion in this book.

CHIEF CAUSES OF FAILURE TO EXCITE IN A SHUNT GENERATOR

(1) Loss of residual magnetism.
(2) Too low a speed.
(3) Wrong connection of field coils relative to armature.
(4) Wrong direction of rotation.
(5) Too high a resistance in the shunt field circuit.
(6) Wrong brush position.
(7) Dirt or grease on the commutator (the dirt acts as an insulator for the small voltage due to residual magnetism which sends the initial current through the field coil).
(8) Disconnection in the field circuit.
(9) Too low a resistance in the load circuit (if any) across the terminals of the machine.

In concluding this section, it is well to point out that a good knowledge of the shapes of the characteristic curves of generators, and of the reasons leading to these shapes, is of great importance to the electrical engineer since it enables him to pick out the most suitable type of machine for any particular sphere of operations.

MODERN PRACTICE AS REGARDS STRUCTURAL DETAILS

Machines now being made are commonly of the multipolar type having circular yokes. Motors are usually provided with end shields carrying the bearings and enclosing the working parts to a considerable extent. The degree of enclosure depends a great deal on the working conditions likely to be experienced, thus, if the situation in which the motor is to be installed is dirty or damp, total enclosure will be adopted, though this will limit the cooling capacity of the carcase and result in higher cost for a certain rating. When working conditions are more favourable the end shields may be of a more open type, giving greater possibilities in the way of ventilation and cheapening the machine.

The general scheme of construction is shown in Figure 104, the paths of the magnetic lines being indicated by the dotted lines. The yoke Y is usually made of mild cast steel, though occasionally cast iron may be used. If the yoke is of cast steel, the poles may be made of the same material and cast with it, the alternative method being to build the poles of laminations and bolt them to the yoke. The pole shoes will invariably be laminated and may consist of extensions of the pole laminations. If the poles are of cast material, the pole shoes will be assembled separately and bolted to the poles. The use of shoes, having a considerably greater face area than the area of cross-section of the poles, is to permit the use of high flux densities in the poles and lower flux densities in the air gap.

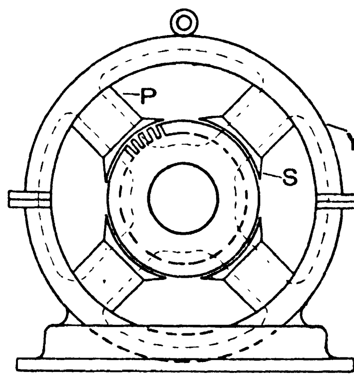


FIG. 104.

For large dynamos, which commonly work under very favourable conditions, a more open type of construction is often adopted, the bearings being contained in separate pedestals mounted on the bed plate which carries the yoke as indicated in Figure 111.

There are two distinct factors which may limit the output which can be obtained from a motor or dynamo carcase of given size—one is the possibility of undue sparking at the commutator and the other is the possibility of undue heating. The possibility of sparking can be much reduced by the use of small commutating poles, situated between the main poles, and these are now almost universally used except in small machines (see page 174). Since the advent of commutating poles, the possibility of undue heating has become the more important factor in limiting the output from dynamos and motors, and in recent years much attention has been paid to the improvement of the ventilation of machines. Whenever possible axial and radial ventilating ducts are provided in the armature and steps taken to force through these ducts an

adequate supply of cool air, fans often being placed on the end of the armature to give the desired result. Bush type bearings with ring oiling are still used, but ball and roller bearings are becoming more common, the diminution in friction loss being of great advantage. Brushes are universally of carbon, mainly on account of their advantage in suppressing sparking. The most important requirements for carbon brush-holders are

(1) Good path for current when passing from brush to brush spindle.
(2) Low inertia of moving parts.
(3) Constancy of brush position on the commutator as the brush wears.
(4) Ease of replacement of brush.
(5) Ease of adjustment of mechanical pressure on the brush.

Figure 105 shows an example of the hinged arm type of brush-holder. The boss B is firmly secured to the brush-holder arm H and the arm A, carrying the brush C, can swing

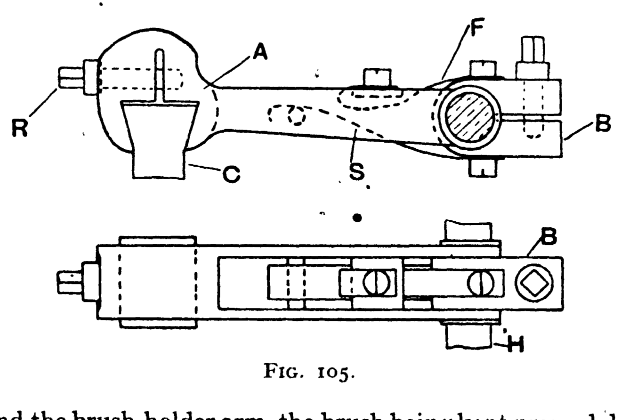


FIG. 105.

round the brush-holder arm, the brush being kept pressed down on to the commutator by the spring S. The flexible connection F is employed to assist in conveying current to the brush-holder arm. Looking at this type of holder in the light of the list of requirements given above, it may be criticised on the score that the moving parts are too heavy, that the path

provided for the current is only of moderate quality and that the position of the brush on the commutator is likely to vary as the brush wears. These defects are common to all examples of this type and modern machines are more usually fitted with brush-holders of a box pattern. An example of this type is shown in Figure 106; the frame F is secured to the brush-holder arm H and the carbon brush C slides moderately loosely in the box frame B, being pressed down on to the commutator by the coiled spring S. The pressure of the brush on the commutator may be adjusted by placing the end A of the spring into one or other of the notches shown. The current is conveyed from the brush to the brush-holder arm by means of the flexible connection E, one end of which is directly secured to the brush. Generally, we may say that defects which are inherent in the hinged arm type of holder are overcome or minimised in the box type. Though modern machines are usually arranged to operate with fixed brush positions at all loads, rockers are still fitted. The rocker has to support brush-holders both of positive and negative polarity, and insulation must therefore be inserted at some point between the brush-holder and the rocker. The usual plan is to insert insulation between the brush-holder arms and the rocker, but occasionally the insulation is inserted between the brush-holder and the brush-holder arm, the latter being covered with a layer of micanite or other suitable material.

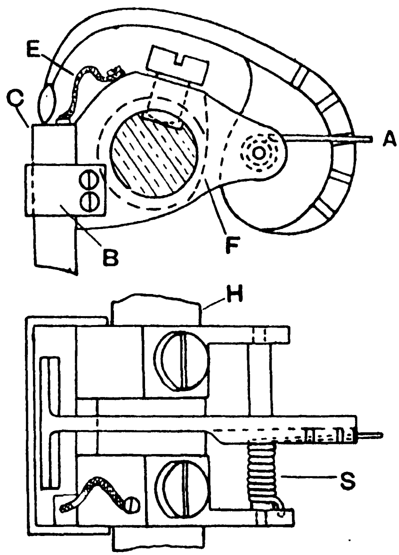


FIG. 106.

Two views of an enclosed ventilated machine, intended for use as a motor, are shown in Figures 107 and 108. They have

been kindly supplied by the Lancashire Dynamo and Motor Co., Ltd., to whom the writer is also indebted for information concerning their arrangement. The yoke is a cast steel drum to which the laminated poles are bolted, both main and commutating poles and their windings being clearly seen in Figure 107. The coils are former wound and the turns are interwoven with tape which, when the whole is treated with an insulating enamel, results in a very solid construction. The armature stampings are held together by steel rings shrunk on while the core is under mechanical pressure, and a fan for ventilating purposes is fitted at the driving end of the machine. The machine is provided with totally enclosed ball bearings at the commutator end and with roller bearings at the driving end, this arrangement ensuring permanent uniformity of the air gaps. Figure 109 shows an external view of an older type of motor by the same Company which is fitted with bush type bearings.

The general details and proportions of a large eight-pole slow speed generator are shown in Figures 110 and 111.

Dealing first with the field-magnet system and frame, the yoke Y (of cast steel) is cast in two halves, and is supported by the bed-plate B, to which are also bolted the pedestals P which carry the bearings Z. The pole pieces X are cast solid with the yoke ring, and are provided with pole shoes shown conventionally at S. The field is compound wound, the shunt coil being shown at A and the series turns at L.

The armature stampings G, which are stamped in segmental form in order to prevent waste of material, are supported by the spider O, and are driven by means of the projections from the spider shown at K. At intervals in the stampings spaces V are left (by means of distance pieces), which serve to improve the ventilation of the core. The depressions shown in the core surface at D are for the binding wires to lie in.

The stampings are held together by means of the end plates E, which are securely bolted to the armature spider. The conductors T are placed in slots, which are not shown in the figure.

The commutator, which is mounted on a separate spider H securely fixed to the armature spider so that no relative motion may take place, consists of copper segments C well

insulated from the supporting spider by the moulded insulating bushes R, and from each other by the mica plates F.

The segments are kept in position by the end plates M, whose peculiar shape prevents them from flying outwards

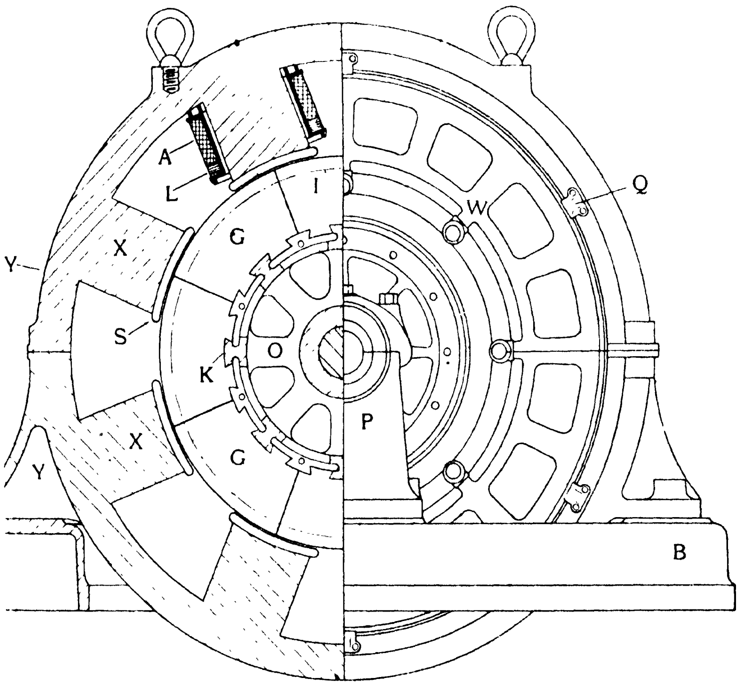


FIG. 110.

owing to centrifugal force, or from being knocked inwards by a blow or by brush pressure.

The segments are connected to the copper conductors by the "risers" U, and the end connections of the armature at the end remote from the commutator are indicated at J.

The brush-holders are attached to the ring W, for which a certain degree of freedom of rotation is provided by arranging for it to slide through the supports Q. Frequently the ring

W is provided with a worm-wheel gearing so that it can readily be moved round (thus displacing the brushes) when required.

The brush-holders and brush-holder arms are not indicated in the figure for the sake of clearness.

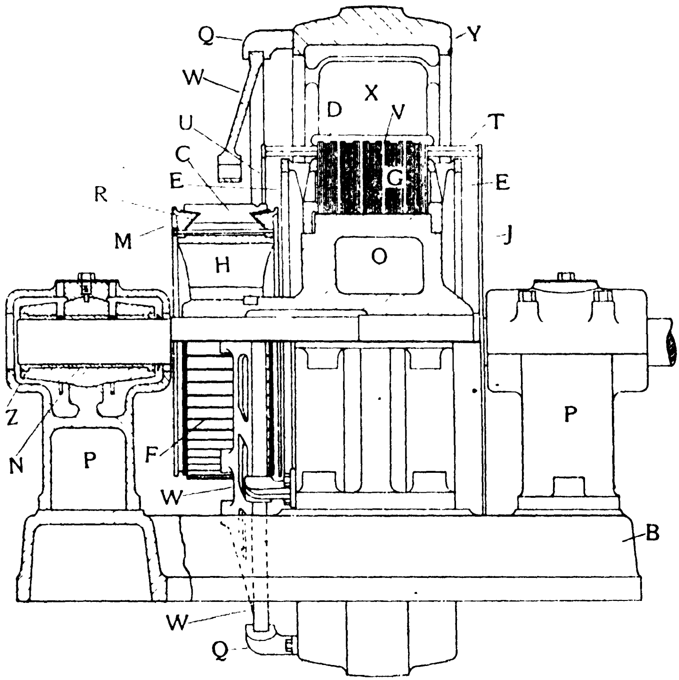


FIG. 111.

ALTERNATING CURRENT GENERATORS

In this type of generator the structural changes are merely modifications required by the special conditions. No new principle is introduced, and in fact we might expect to find greater simplicity, for in the direct current machines already discussed the induced E.M.F. in each active conductor is naturally alternating.

This means no commutator is required, a very important advantage; but it entails a departure from simplicity in

another direction, for the generator can no longer excite its own fields, and therefore an auxiliary direct current machine is required for that sole purpose. It is true that various self-exciting forms of alternator have been suggested, and some progress has been made in the direction of double-current machines, in which the armature windings are fitted with a suitable commutator to supply direct current and are also arranged as in an alternator, thus making the machine self-exciting and enabling both direct and alternating currents to be supplied simultaneously by the same active conductors. Here we shall merely explain how an alternator may be derived from the forms of generator already described.

Let us imagine an ordinary ring-wound armature, rotating

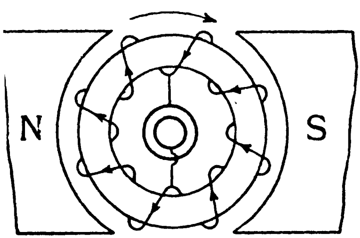


FIG. 112.

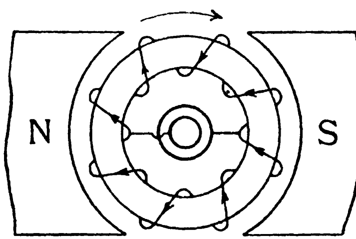


FIG. 113.

in a two-pole field, fitted with two " slip rings " instead of a commutator (i.e. two complete metal rings mounted side by side upon the shaft, but insulated from each other and from the shaft, each provided with a brush to make connection to the external circuit) ; and let two diametrically opposite points on the winding be connected to these rings. Figure 112 shows the arrangement.

If the fields are kept excited from some external source of current the result is a simple form of alternator, and we have now to examine its working to ascertain what objections there are to it in practice, and what modifications are necessary.

At the instant shown in Figure 112 the E.M.F. produced is evidently at its maximum value, for the active conductors in series are placed so that their individual E.M.Fs. are added together, but a quarter of a revolution later, at the instant depicted in Figure 113, half of these conductors are under a

N pole, and the other half under a S pole, i.e. some are moving upwards through the field and some downwards through it, and thus their E.M.Fs. are in opposite directions, the resultant being zero. In the intermediate positions there will be some resultant E.M.F., due to the difference of the two opposite but unequal E.M.Fs., and hence the P.D. between the slip rings decreases gradually from some maximum value in the first position to zero in the second, and then rises gradually until it reaches the same maximum, but in the opposite direction, in another quarter revolution, and so on.

In these figures the active conductors are not grouped to the best advantage, for in all positions except those of maxima the conductors in series are the seat of opposing E.M.Fs., and in the position mentioned many of them are almost inactive. These defects may be overcome and the E.M.F. generated thereby increased by concentrating the turns as in Figure 114.

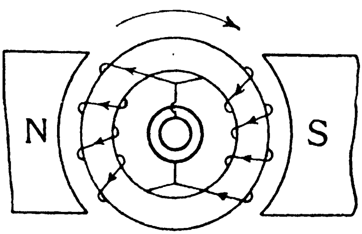


FIG. 114.

Here they are arranged in two groups, which together occupy only half the available space on the armature, and if we make the polar arc equal to half the pole pitch,[1] each belt of conductors will practically escape from the influence of one pole before it comes under the influence of the next.

The result is an alternating E.M.F. which completes one cycle in each revolution. The law, according to which it rises and falls, i.e. the "wave form," depends upon the grouping of the conductors and the exact configuration of the poles, and will not be discussed here.

Such a machine means either very low frequency (i.e. number of complete cycles per second) or excessive speed, and this is perhaps the greatest objection to it; for instance, it must run at 3000 revolutions per minute to give the commonly used frequency of 50 complete cycles per second.

[1] The **polar arc** is the angular breadth of a pole; the **pole pitch** is the angular distance from the centre of one pole to the centre of the next.

It should also be noticed that the particular method of connecting two diametrically opposite points on an armature to slip rings is not the only plan available; we began with it because it is the easiest way of adapting an already wound direct current armature to give a single-phase alternating current. Were it seriously intended to wind an armature as in Figure 114, it might be connected up as in Figure 115.

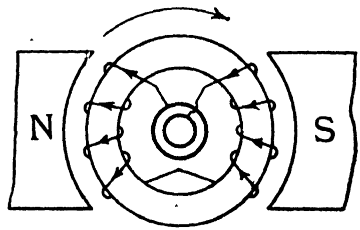


FIG. 115.

This would put all the active conductors in series and would double the E.M.F. obtained at a given speed, but would also obviously halve the output of current.

To obtain a higher frequency it is necessary to perform more than one cycle in each revolution, and this involves an increase in the number of poles. This modifies the design very considerably, and enables us to pass from the two-pole direct current machine to actual types of alternators.

The exact number of poles required in a given case is independent of the size or output, and is determined by the speed at which the machine is to run and the frequency to be obtained. When the speed is necessarily great, as in turbine-driven alternators, there is no difficulty about frequency, and a two-pole machine as above might be used. In practice, however, four-pole fields and six-pole fields are also employed.

The ring winding may be extended to multipolar forms as in Figure 116, which shows how the coils must be connected in order to put all the active conductors in series. With this number of poles there will be three complete cycles per revolution. It may be pointed out in passing that it is unsafe for a beginner to calculate frequency merely from the number of poles, for this depends also upon the type of field magnet used. It is, however, always safe to reckon from the number of groups of active conductors on the armature, for each group must pass into the position of the next but one before it in order to complete a cycle, so that the number of cycles

per revolution is half the number of groups, and we have the expression

frequency = ½ *number of armature groups* × *rev. per sec.*

We are now led to consider another new feature to be met with in A.C. generators. In D.C. machines we may say it is the universal practice to have the field-magnet system fixed and the armature movable; this is on account of the com-

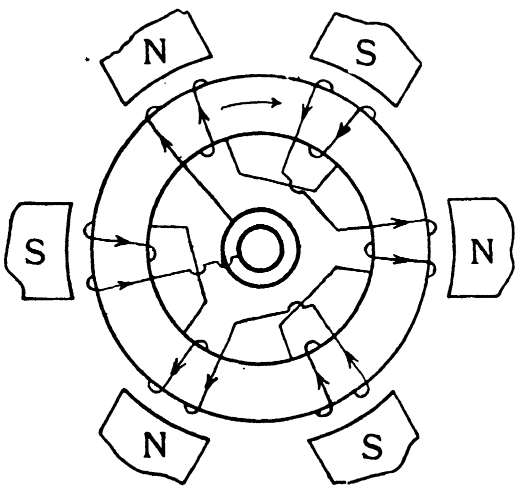


FIG. 116.

mutator; but in A.C. machines, in which there is no commutator, this restriction no longer holds good, and in fact alternators with a moving field system and a fixed armature possess important constructional advantages over those with moving armature and fixed field magnets.

In the first place it is necessary in practice to build alternators for much higher voltages than are met with usually in D.C. machines, and this introduces a serious difficulty as regards the efficient insulation of the armature conductors from each other and from the frame of the machine, and students remembering the mechanical poorness of the insulating materials available will realise that these difficulties

are much more readily overcome when the armature is fixed than when it is moving.

Then again there is the important question of the collection of the current. If the armature is moving the current will have to be collected by slip rings, which may be troublesome, whereas if the armature be fixed, these are done away with.

Of course, in the latter case, the direct current for exciting purposes has to be conveyed to the moving field system by means of slip rings, but this current is comparatively small and the voltage low. In fact, the moving field type is at the

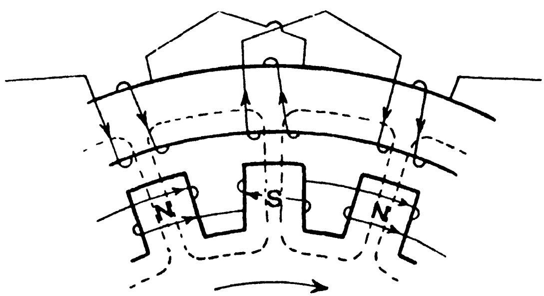


FIG. 117.

present time pre-eminent for large outputs, and as space is limited we shall restrict ourselves to it.

Still keeping to the ring winding the design now becomes as shown in Figure 117.

But we know the ring winding is only a particular way of joining up the groups of active conductors lying under the pole faces, and necessarily involves much idle wire, apart from other objections, so that there is much to be gained by substituting a more direct connection. This is shown most clearly by drawing the active conductors as seen projected on the pole face.

These diagrams apply equally well whether the poles are internal or external. The result is a kind of drum winding, of which two varieties are shown in Figure 118.

The upper form has as many coils as poles; the second, sometimes called a "hemitropic" winding, has half as many coils as poles. Electrically speaking they are equivalent, and

their choice is mainly a question of convenience, although as the end connections in the second form are somewhat longer, there will be rather more idle wire and slightly greater armature resistance. Only a few conductors are shown for

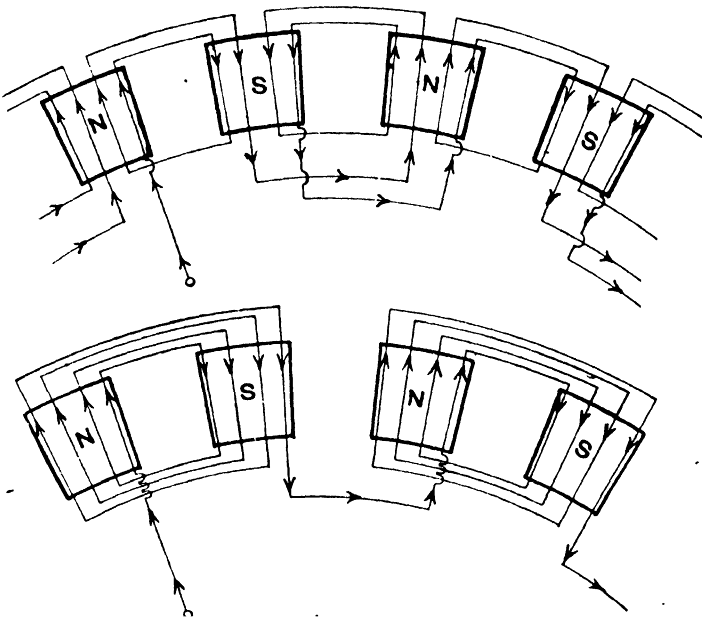


FIG. 118.

the sake of clearness, but evidently any number may be thus grouped.

Some details of the construction of actual machines are shown in Figure 119.

Figure 119a shows the outwardly projecting radial poles NS bolted to the rim of a cast iron or cast steel flywheel. This rim forms the yoke of the magnetic circuit and the flywheel itself is securely keyed to the shaft.

The poles may either be made up entirely of soft iron laminations bolted together, or, as in Figure 119*b*, may consist of a wrought iron or cast steel body M secured to the flywheel

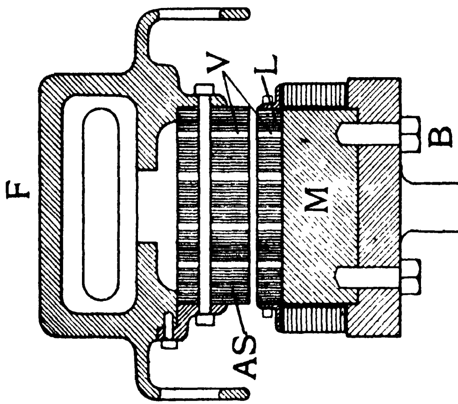


Fig. 119b.

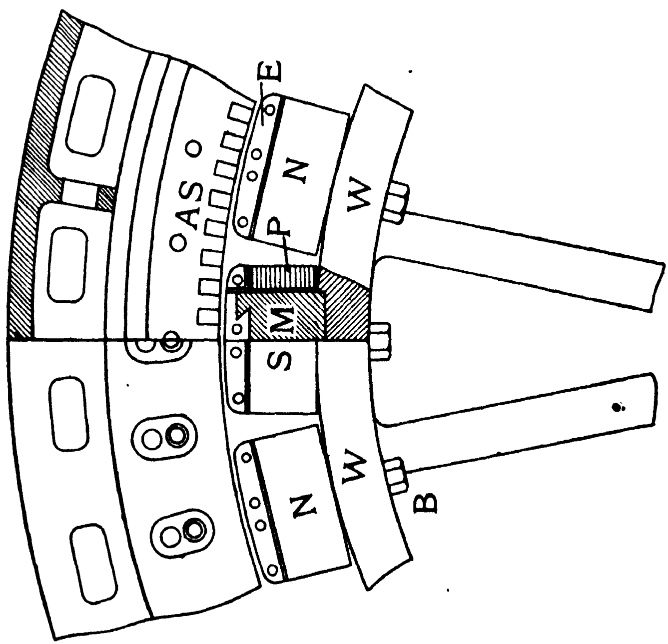


Fig. 119a.

APPENDIX I TO CHAPTER VIII

NOTE ON COMMUTATION IN D.C. MACHINES

Hitherto we have supposed the armature to be rotating in a fairly uniform field due to the field magnets, in which case the positions of zero-induced E.M.F. (and therefore of the brushes) will be midway between the pole tips.

But in actual practice it is found that the brushes must be given a "lead," i.e. advanced in the direction of rotation by some small amount beyond the midway point; and further, that the amount of lead required increases with the load, any departure from the correct position giving rise to more or less sparking. In the case of a motor the general facts are the same, except that a backward lead is required.

For many practical purposes it is imperative that these natural tendencies should be suppressed, and that the machines should operate sparklessly with fixed brushes; and we have now to consider the nature of the difficulty and its remedy from a quite elementary and necessarily incomplete point of view.

There are two questions to be dealt with: (1) Why "lead" is required; (2) the actions going on at the brush.

As regards (1) it is only necessary here to point out that, although the exciting field may be uniform when the armature is running without load, it is quite different as soon as the armature conductors carry current. Then the iron core becomes an independent electro-magnet with lines of magnetic flux emerging at and near the brush positions (for a reference to Figure 86 will show that it is equivalent to two semicircular electro-magnets with their "like" poles placed in contact, the positions of the poles depending on the position of the brush), and these lines will return mostly through the closely adjacent pole pieces.

Hence in the air gap there are superposed two magnetic fields of different origin; the main field as we have hitherto understood the term, and the field due to what is known as the *cross-magnetizing effect* of the armature current.

Figure 121 shows the two fields in a very rough diagrammatic form, only a few lines being drawn for convenience, and the general path being merely indicated. The actual direction of the resultant field in the iron is unknown and immaterial; we are concerned only with the air gap, and there we notice that at A

and A_1 the two fields strengthen each other, and at B and B_1 they weaken each other. The total strength is so far unaltered, but the net effect is exactly as if the field had been dragged round a little in the direction of rotation as in Figure 122 (in a motor

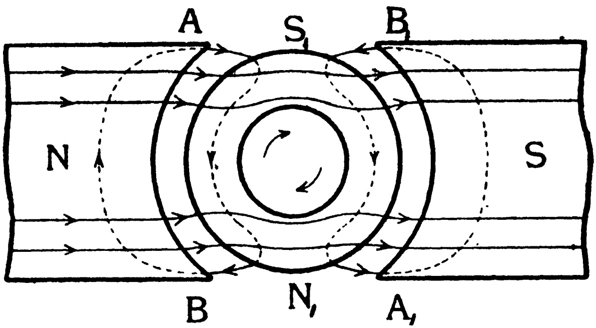


FIG. 121.

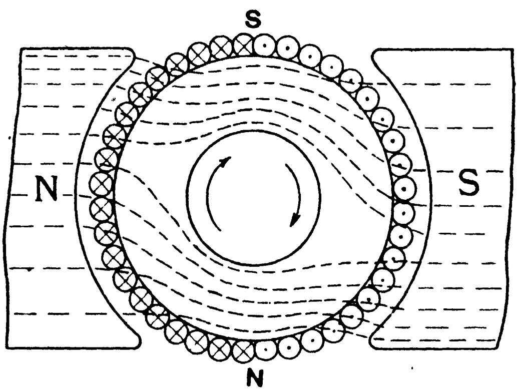


FIG. 122.

it would be in the opposite direction), and as a result the position of zero induced E.M.F. (called the neutral point) is advanced by a corresponding amount. In consequence the brushes must be similarly advanced, or else sparking more or less pronounced occurs. If the load increases, so do the cross-magnetising ampere-turns of the armature, and the brushes must be still further advanced.

These actions are perfectly natural and unavoidable, and it

might be inferred that sparkless running with fixed brushes is impossible. But at the same time it will be apparent that the range of lead required is to a certain extent under control, for by making the main field as strong, and the armature field as weak, as possible (i.e. few conductors on armature), the disturbance due to the latter is minimised, and the change of position between no-load and full-load made very small.

In this brief statement we have only attempted to show why lead is required, and in no way to discuss adequately the subject of "armature reaction" generally.

We have now to deal with the actual causes of sparking.

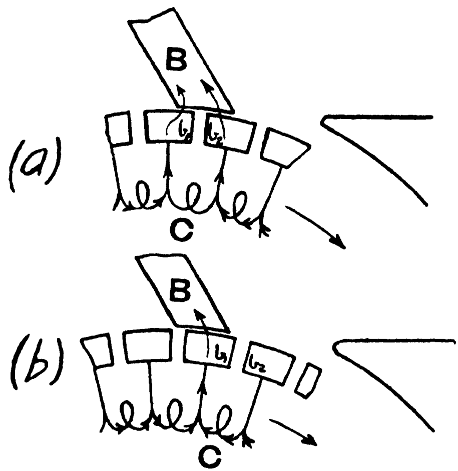


FIG. 123.

Consider any one group of armature conductors, i.e. a section or coil containing one or more active conductors. A moment before it reaches the brush it is carrying a certain current, varying according to the load, and the instant it passes the brush it will have to carry an equal current in the opposite direction. In Figure 123 (*a*) the coil in question is marked C. At the instant shown it is just passing the brush; the current from the left is flowing through the bar b_1 into the brush; the current from the right is flowing through the bar b_2 into the brush; the coil C itself being momentarily out of the circuit. The next instant, however, the bar b_2 will slip from under the brush as shown in Figure 123 (*b*), and if at that instant there is any current worth

mentioning flowing from b_2 into B, then there will be a spark more or less marked at the moment of breaking contact.

Looking at (*a*) we see that really two paths are available for the current from the right at the moment in question. It can take the direction shown, b_2 to B, but it can also flow through C into b_1 and thence to B, these two paths being in parallel, and to obtain good commutation we must make the current from the right increase through the second path and diminish through the first, until at the instant b_2 breaks contact with B the whole current is flowing through C to b_1, and none from b_2 to B.

Having thus stated the problem, let us follow the fortunes of the coil C as it comes up from the left.

As soon as b_1 touched B it was cut out of circuit, and the current in it naturally began to die away. But we know that when a current in a coil is stopped, an induced E.M.F. is set up in it acting in the same direction and tending to keep it from dying away instantly. (This induced E.M.F. is often called the "reactance voltage.") No sparking occurs at this instant, because, as a glance will show, the coil C is now short-circuited by the brush, and if only a small but definite amount of time be given the current will die away naturally dissipating its energy as heat in this local circuit.

The greater the load current the greater will be the induced voltage tending to retard its disappearance, and it becomes necessary to provide some means of accelerating the process.

Two distinct methods are available. In practice, both are to some extent operative simultaneously, but it will be convenient to consider them separately.

The first is to impress upon the coil whilst short-circuited by the brushes another E.M.F. in the opposite direction to the reactance voltage. This can be done by slightly increasing the lead of the brushes until they are in advance of the neutral point, and in practice, as there is nothing to mark the position of the latter, they are simply advanced until sparking disappears or is reduced to a minimum. The active conductors are now cutting magnetic lines while short-circuited, and the E.M.F. thus produced not only enables the current to die away more rapidly by neutralising the reactance voltage, but also tends to start a current in the opposite direction, i.e. in the direction actually required on the right-hand side of armature. It is true this induced E.M.F. is not great, but on the other hand the resistance of the short-circuit path through the coil is low, and therefore the current thus produced may be of considerable magnitude ; if it becomes equal to the working current at the instant b_2 slips from under B the commutation is practically sparkless.

In fact, by considering such a current superposed upon the coil C in Figure 123 (*a*), it will be seen that all this really amounts to saying that the presence of a reversing E.M.F. in C tends to make the current increase in the path Cb_1B and diminish in the path b_2B, which is exactly what is required.

This method of reversal is often called "E.M.F. commutation." It depends entirely upon the existence of a sufficiently strong reversing field at the brush positions, and if this field could be made to increase in strength as the load increases the latter might remain fixed. But as shown in Figure 122, the field at this point

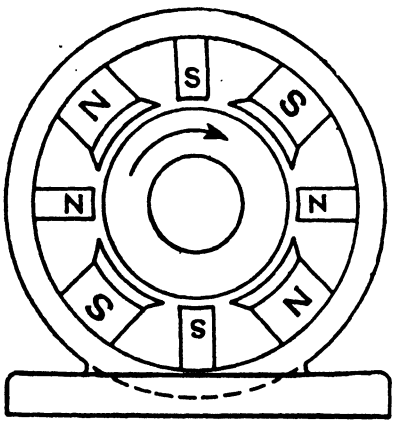


FIG. 124.

actually decreases as the load increases on account of the cross-magnetising effect of the armature, hence the brushes must be advanced to make up for it; and if the load exceeds a certain value, even this remedy fails, and sparkless commutation becomes impossible (assuming that the heating limit is not previously reached).

E.M.F. commutation is also employed, in a more convenient and efficient way, in machines to which commutating poles are fitted. In Figure 124, which represents a dynamo, we see that between the main poles of the machine, small auxiliary poles are fitted and excited so as to have the same polarity as the main pole immediately in front. The brushes are placed so that commutation takes place when the coil concerned is passing under one of these commutating poles. The commutating poles are arranged to be of such strength and polarity as will give an E.M.F in the

short-circuited coil which is approximately equal in magnitude, but opposite in direction, to the reactance voltage due to the inductance of the coil; reversal of current in the coil undergoing commutation is thus considerably facilitated.

The reactance voltage is proportional to the magnitude of the current to be reversed, and by arranging the commutating poles so that they do not become magnetically saturated and providing them with a winding connected in series with the armature, it is possible, over a considerable range of load, to provide the correct value of generated voltage in the short-circuited coil for any load. In a motor the polarity of the commutating pole needs to be of the same kind as the main pole immediately behind, but if the commutating pole winding is correctly connected relative to the armature for running as a dynamo, it will, without change of connection, also give the correct polarity for running as a motor in either direction (assuming the brush position not to be altered).

The second method is called "resistance commutation." This involves the use of carbon brushes made wide enough to bridge over several segments of the commutator at once, the special virtue of carbon being that the "contact resistance" between brush and commutator is something like ten times as much as for metal brushes. By using a wide brush a longer time is afforded for commutation, for we are not now supposed to have the assistance of a reversing E.M.F. As several coils are out of action at once, the P.D. between terminals of the machine will be slightly less, and the increase of brush resistance will have a similar effect; but these drawbacks are negligible in view of the advantages gained.

As regards the mode of reversal in this case, first, the extra time allowed by the wide brush enables the current to die away naturally, dissipating its energy as heat, and this process takes place the more readily in that the coil C is no longer short-circuited through an almost negligible resistance, but through the two carbon-metal contacts and the material of the brush in which most of the heat is produced.

Looking at Figure 125, we see that, as already mentioned, there are now two paths in parallel available for the current from the right, one through b_2 and into the brush, the other through the coil C to b_1, and thence into the brush; and the current will tend to divide up inversely

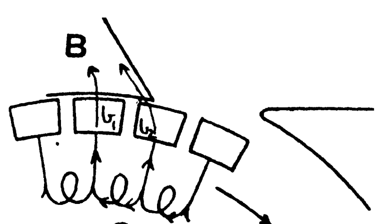


FIG. 125.

as their respective resistances. But the contact area between b_2 and B is decreasing, and therefore the resistance of that path is increasing, whilst that of the other path remains constant, and as a result the current tends more and more to become diverted from the first path into the second, this being exactly what is wanted. Hence at the moment b_2 emerges from the brush there may be little or no current through it to be broken, and in any case carbon is a good material to assist in suppressing what little sparking may occur.

These processes require merely time and contact resistance, and are independent of the position of the brush within reasonable limits, so that if only the machine is reasonably well designed to begin with, the brushes may remain fixed in position at all working loads.

We have, in the above notes, indicated two distinct methods whereby commutation may be secured. In modern machines, using commutating poles and carbon brushes, both methods are simultaneously helping to give the desired result.

It may be pointed out that each stoppage of current in a coil involves loss of energy, just as if a moving body had been pulled up. In resistance commutation this energy is completely lost as heat, whereas in E.M.F. commutation it is not all lost, for much of it may be usefully expended in driving the armature. This is because the current dies away in a field of force opposite in direction to that in which it was produced, and therefore the mechanical force which previously retarded motion becomes reversed in direction, and tends to turn the armature in the way it has to go.

APPENDIX II TO CHAPTER VIII

NOTE ON MAGNETIC THEORY

Force on conductor in magnetic field.—A reference to the definition of unit current on page 74, and to the definitions and conventions relating to magnetic force and magnetic flux density on page 73, will show that a conductor 1 cm. long carrying a current of one absolute unit, and situated in a magnetic field of unit strength (the lines of the field being at right angles to the conductor), is acted on with a mechanical force of 1 dyne. Further, it is reasonable to suppose, and the supposition can be verified experimentally, that the magnitude of the force on the conductor in any case will be co-jointly proportional to the magnitude of

the current, the length of the conductor and to the strength of the magnetic field. We therefore arrive at the formula for the force on a conductor.

$$F = BIl \text{ dynes, where}$$

B is the flux density in lines per square cm.,
I is the current in the conductor in absolute units, and
l is the length of the conductor in cms.

If the current is in amperes the formula becomes

$$F = \frac{BIl}{10} \text{ dynes,}$$

$$= \frac{BIl}{10 \times 981} \text{ grs. wt.,}$$

$$= \frac{BIl}{10 \times 981 \times 453 \cdot 6} \text{ lbs. wt.}$$

E.M.F. generated when a conductor cuts lines of magnetic flux.—It has been stated on page 87 that when a conductor cuts one line of magnetic flux per second an induced E.M.F. of one absolute unit is produced, and, further, that this idea may be used as a definition of the absolute unit of E.M.F. alternative to that given on page 75. In order to show that this statement is correct, consider a conductor whose length is l cms. moving at right angles to the magnetic lines of a field whose strength is B lines per sq. cm. with a velocity of S cms. per second. Further, suppose that the conductor forms part of a closed circuit and that as a result of the E.M.F. generated within it, a current of I absolute units is produced. From the last paragraph it will be realised that a force of BIl dynes will act on the conductor in such a direction as to oppose the motion and the work done per second to drive the conductor will be $BIlS$ ergs.

Applying the principle of the conservation of energy, it will be realised that this work reappears in the electrical circuit and its magnitude in terms of the electrical quantities will be IV ergs per second. We thus have $IV = BIlS$ or

$$V = BlS \text{ absolute units.}$$

A little thought will show that BlS is the number of lines cut per second, or if one line is cut per second the generated E.M.F. will be 1 absolute unit.

If, instead of thinking of a straight conductor cutting a magnetic field, we have in mind a coil of one or more turns through which the total flux is changing (as in a transformer coil) we may express the result of the above investigation in a slightly different manner. If only one turn is involved, the E.M.F. generated will be equal to the rate of change per second of the number of lines

linking with the turn. If the coil has more than one turn we say that the E.M.F. generated is equal to the rate of change per second of the number of linkages, the number of linkages being found by multiplying the number of turns by the flux passing through them. It will be realised that a rate of cutting of lines of 10^8 per second, or a rate of change of linkage of 10^8 per second, will give a generated E.M.F. of 1 volt.

Magneto-motive Force.—The terms magnetic force and magnetic flux density, which have already been defined, refer to the conditions of affairs at a given point but, in many cases, we desire to study a complete magnetic circuit and in this connection we find a use for the expression Magneto-motive Force. Consider the simple magnetic circuit shown in Fig. 126, which consists of a ring of circular cross-section. This shape is often referred to as a toroid or anchor-ring. Let the length of the magnetic circuit (i.e. the mean circumference of the ring) be l cms. and let it be uniformly overwound with N turns each carrying a current of I absolute units. If we consider any point on the mean circumference of the ring, there will exist at that point a definite value of magnetising force which we will call H. Now the total tendency of the coil to send a flux round the ring will depend upon the value of H (which in this simple case is constant in value all round the mean circumference) and also upon the length of path (l) over which this value of magnetising force is exerted. This total tendency is referred to as the Magneto-motive Force of the coil (usually abbreviated to M.M.F.) and is equal to Hl in the case under notice. In less simple cases the value of H is likely to vary from point to point along the magnetic path and we should then write M.M.F. $= \Sigma Hl$, this expression implying that we are dividing the full path into a convenient number of parts (over each of which H is uniform) and summing up to get the total result. Returning to the simple toroid, if we imagine the core to be air and that a unit pole is placed at any point of the magnetic path, there will be a force of H dynes exerted on the pole and, if we move it round the magnetic circuit against this force, the work done will be Hl ergs. We see, therefore, in this simple case, that

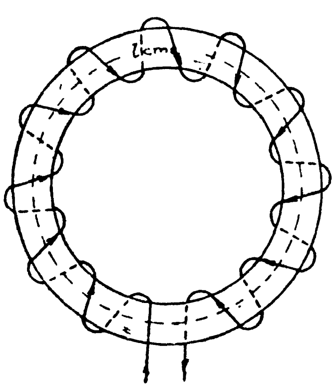


FIG. 126.

the M.M.F. due to the coil is numerically equal to the work (in ergs) done when the unit pole is forced round the circuit. The M.M.F. is not, however, referred to as so many ergs per unit pole, but as so many " gilberts."

If we wish to derive an expression for the M.M.F. of the coil wound on the ring, we note that if the unit pole is taken round the magnetic circuit in a direction against the mechanical force acting upon it, Hl ergs of work will be done and the M.M.F. of the coil will be Hl gilberts. This work reappears in the electrical circuit and may be ascertained as follows: Suppose the pole to make its tour of the magnetic circuit in a time t seconds, the 4π lines of flux which emanate from the pole will cut each of the turns of the coil and the average value of the generated E.M.F. will be $\frac{4\pi N}{t}$ absolute units. This E.M.F. will assist the current to flow and the work appearing in the electrical circuit as a result will be $\frac{4\pi N}{t} \times I \times t = 4\pi IN$ ergs.

Thus we may say that the M.M.F. due to the coil will be $4\pi IN$ gilberts.

If the current is expressed in amperes the formula becomes

M.M.F. $= 0{\cdot}4\pi IN$ gilberts $= 1{\cdot}257$ IN gilberts.

It is not possible to go deeply into the matter in an elementary book, but, as a matter of fact, this expression for M.M.F. is true no matter what the disposition of the turns on the magnetic circuit may be.

Formulæ for magnetising force.—In certain cases where H is uniform round the magnetic circuit, as in the case of the anchor ring, we may use the general formula for M.M.F. to deduce particular formulæ for magnetising force, thus in the case under notice we have

$$Hl = 1{\cdot}257 \text{ IN or } H = \frac{1{\cdot}257 \text{ IN}}{l} \text{ gilberts per cm.}$$

So far we have had in mind the state of affairs for the magnetic path passing through the axis of the ring. Other magnetic paths will pass near the inner and near the outer circumferences of the ring. The M.M.F. will have the same value for all these paths, but the corresponding values of magnetising force will vary owing to the varying lengths of magnetic path over which the M.M.F. is exerted.

The formula obtained for H in the case of the anchor ring is also approximately true in the case of a straight solenoid whose length is many times its diameter.

Effect of an iron core.—If the anchor ring is provided with an iron core in place of an air core, the expressions for M.M.F. and magnetising force will remain unaltered. The flux density and total flux round the ring will, however, both be considerably increased, the new flux density being found by multiplying the magnetising force by the permeability.

The relationships of the various quantities involved will be appreciated by a study of the following examples:

Example.—A ring of circular section, external diameter 32 centimetres, internal diameter 24 centimetres, is composed of wrought iron and wound with 400 turns. What current will be necessary to produce a flux of 176,000 lines within the iron?

(The word **Flux** is used to denote the total number of lines within the iron, so that if A = area of section of iron, then Flux $= B \times A$, or $B = \frac{\text{Flux}}{A}$.)

As the radius r of the iron core is 2 centimetres and $A = \pi r^2$,

we have $A = \frac{22}{7} \times 2 \times 2 = \frac{88}{7}$ sq. cms.

$$\therefore B = \frac{176000}{\frac{88}{7}} = 14{,}000 \text{ lines per sq. cm.}$$

Note that this value of flux density is the average flux density. Really the flux density will not be quite uniform over the cross-section of the ring, being somewhat greater near the inner circumference on account of the higher value of H in this region.

Now $Hl = 1{\cdot}257$ IN or $IN = 0{\cdot}8\ Hl = \frac{0{\cdot}8\ Bl}{\mu}$.

Reference to the permeability curve for wrought iron on page 145, shows that when B = 14,000 lines per sq. cm., $\mu = 800$, and we have, therefore,

$$IN = \frac{0{\cdot}8 \times 14{,}000 \times 3{\cdot}14 \times 28}{800} = 1232 \text{ ampere-turns.}$$

$$\text{Since } N = 400,\ I = \frac{1232}{400} = 3{\cdot}08 \text{ amperes.}$$

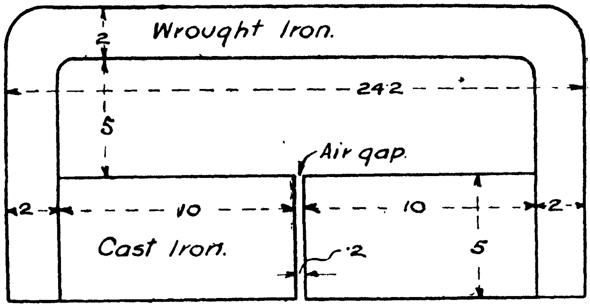
Although we have founded the argument upon the consideration of a simple case, the method applies to all problems in which the path of the lines of flux is of fairly definite section. A rather more complicated example is considered below.

Example.—Calculate the ampere-turns necessary to produce a flux of 100,000 lines in a magnetic circuit of the dimensions given in Figure 127, consisting of two pole pieces of cast iron, each 10 centimetres long and 5 centimetres square in section; an air

gap of the same section and 2 millimetres wide; and a yoke of wrought iron, whose section is 5×2 sq. centimetres.

For the cast iron and air gap $B = \dfrac{100{,}000}{25} = 4000$ lines per sq. cm.

For the wrought iron $B = \dfrac{100{,}000}{10} = 10{,}000$ lines per sq. cm.



Thickness at right angles to paper 5cms.
All dimensions in cms.

FIG. 127.

On referring to the curves on page 145, we find that at these flux densities $\mu = 2000$ for wrought iron and 750 for cast iron. Also the mean length of the path of the lines in the wrought iron is 41·2 centimetres. Hence we have—

$$\underset{\text{(wrought iron)}}{\text{IN}} = \frac{0{\cdot}8\,Bl}{\mu} = \frac{0{\cdot}8 \times 10000 \times 41{\cdot}2}{2000} = 164{\cdot}8 \text{ ampere-turns.}$$

$$\underset{\text{(cast iron)}}{\text{Ditto}} = \text{ditto} = \frac{0{\cdot}8 \times 4000 \times 20}{750} = 85 \quad \text{,,} \quad \text{,,}$$

$$\underset{\text{(air gap)}}{\text{Ditto}} = \text{ditto} = \frac{0{\cdot}8 \times 4000 \times {\cdot}2}{1} = 640 \quad \text{,,} \quad \text{,,}$$

$$\underline{\underline{889{\cdot}8}} \quad \text{,,} \quad \text{,,}$$

We have assumed that the flux passes across the air gap without appreciable lateral spreading of the lines. This assumption is approximately correct when the gap is very short relatively to its sectional area, as in the present case, but the method would be inadmissible in the case of a longer gap. We have also assumed that no "magnetic leakage" occurs at any point, i.e. that all the lines of flux follow the prescribed path through the iron. This again is not strictly correct and the error (which depends on the distribution of the winding and may be very small) would

be estimated and allowed for when needful. The student should note the enormous relative importance of the air gap in increasing the ampere-turns required.

Ampere-turn per unit length Method of Calculation.—When many calculations of the above kind have to be made it is advantageous to use a graphical method. Starting with the equation $IN = \frac{0 \cdot 8\ Bl}{\mu}$, we notice that $\frac{B}{\mu} = H$. $\therefore IN = 0 \cdot 8\ Hl$.

Let $l = 1$ centimetre, then $IN = 0 \cdot 8\ H$. This means that $0 \cdot 8\ H$ ampere-turns per unit of length are required to produce that value of B corresponding to H for the particular kind of

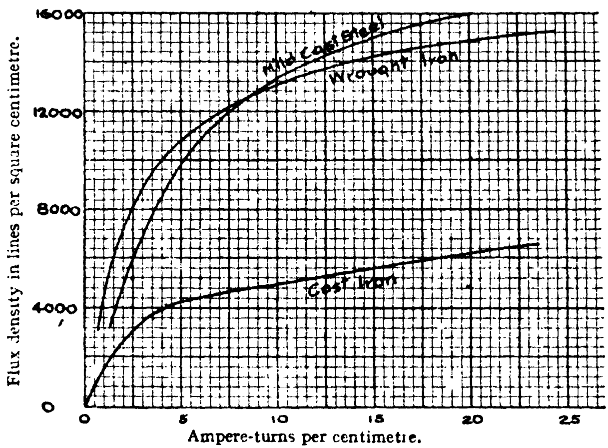


FIG. 128.

iron used. For instance, consider an ordinary magnetising curve connecting B and H for wrought iron, as in Figure 94, and suppose it is required to produce $B = 14{,}000$ in the iron ring example already given, page 180. On referring to the curve we find $H = 17 \cdot 5$, and we see that $0 \cdot 8 \times 17 \cdot 5$ ampere-turns per centimetre of length are required. Now the actual length is 88 centimetres, and therefore $IN = 88 \times 0 \cdot 8 \times 17 \cdot 5 = 1232$ ampere-turns as before. We give this example to show the nature of the method, but to make it really useful we must plot a new curve with B for ordinates, and the ampere-turns per unit length for abscissæ. This is easily done if for every value of H in the original curve we substitute $0 \cdot 8\ H$. Thus, where $H = 50$, we plot 40 ampere-turns per unit length. Such curves are given in Figure 128 for the materials

commonly used in field magnet construction. These have been derived, in the manner indicated above, from the curves connecting B and H in Figure 94.

The following table gives the result of applying the method to the magnetic circuit dealt with in the last example :—

Name of part.	Material	Total Flux. Lines.	Sectional area of part. sq. cms.	Flux Density (B). Lines per sq. cm.	Ampere-turns per cm.	Length of part cms.	Total ampere-turns for part.
Yoke	W.I.	100,000	10	10,000	4	41·2	164·8
Pole pieces	C.I.	100,000	25	4000	4·25	20	85
Gap	Air	100,000	25	4000	3200	0·2	640
				Total ampere-turns = 889·8			

Note that the number of ampere-turns per centimetre for the air gap is not obtained from a curve. We *could* plot a curve for air, but it would be simply a straight line, and would also be very low on the diagram. Greater accuracy is obtained by using the fact that for air 0·8 H = 0·8 B, so that we have only to multiply the required value of B by 0·8, which is often termed the "gap coefficient," in order to obtain the ampere-turns per cm.

Magnetic Reluctance.—Considering a simple magnetic circuit (as a toroid) we see that

$$H = \frac{1 \cdot 257\ IN}{l},$$

$$B = \mu\ H = \frac{1 \cdot 257\ IN\ \mu}{l} \text{ and}$$

$$\phi = \text{total flux} = BA = \frac{1 \cdot 257\ IN\ \mu\ A}{l}$$

$$= \frac{1 \cdot 257\ IN}{\frac{l}{A\ \mu}}.$$

This is an equation similar in form to that expressing Ohm's Law for current circuits, if we regard the ampere-turns as the measure of a compelling force which produces a certain flux in a path defined by $\frac{l}{A\ \mu}$; an expression which reminds us of electrical resistance, and which suggests that μ can be regarded as the inherent magnetic conductivity of the material. From this point of view the denominator $\frac{l}{A\ \mu}$ is known as the **Magnetic**

Reluctance of the circuit, the numerator 1·257 IN being the **Magnetomotive Force.**

Thus, $$\text{Flux} = \frac{\text{Magnetomotive Force}}{\text{Magnetic Reluctance}}$$

There is no real similarity between the electrical and magnetic circuits; it is merely a superficial resemblance in the forms of the equations which can be turned to useful account. When the magnetic circuit is of the kind shown in Figure 127, we can sum up the reluctances of each portion as we sum up resistances in using Ohm's Law, and thus we can arrive at the total reluctance of the magnetic circuit. The equation then becomes

$$\text{Flux} = \frac{1{\cdot}257\ \text{IN}}{\dfrac{l_1}{A_1\mu_1} + \dfrac{l_2}{A_2\mu_2} + \dfrac{l_3}{A_3\mu_3} + \text{etc.}}$$

This expression is seldom convenient in electrical engineering calculations, but is of importance because it brings out clearly the factors which determine magnetic reluctance. It shows that in order to produce a large flux with few ampere-turns we must use iron paths of short length, ample sectional area, made of material of high permeability.

The following table shows flux densities commonly used in field magnets, etc., for dynamos and motors:

Name of part.	Material.	Usual Flux Densities		Remarks.
		Lines per sq. cm.	Lines per sq. inch.	
Yoke ,,	Cast iron Cast steel	6000 to 7500 14,000 to 15,000	40,000 to 50,000 90,000 to 100,000	
Pole pieces ,, ,,	Cast steel Sheet steel Sheet iron	15,000 to 17,000	100,000 to 110,000	High flux densities used to keep down area of section, and also the length of turn of the winding.
Air gap	Air	7000 to 10,000	45,000 to 65,000	
Armature teeth	Sheet iron	15,000 to 20,000	100,000 to 130,000	High density on account of lack of space.
Armature core	Sheet iron	11,000 to 12,500	70,000 to 80,000	Low densities to keep down core loss.

APPENDIX III TO CHAPTER VIII

ADDITIONAL NOTE ON INSULATING MATERIALS

It is desirable, on account of their great practical importance, to summarise briefly the chief properties to be looked for in all such substances. (At the same time it must be remembered that the requirements to be satisfied by any given material depend largely upon the purpose for which it is to be used.)

These properties are :—

(1) High resistivity.

(2) High disruptive strength.

This is a measure of the value of a material as regards resisting puncture or breakdown under applied voltage, and may be expressed by stating the voltage required to puncture a given thickness : it must be recognised as being quite distinct from the first property, and many substances excellent in regard to the one are comparatively poor as regards the other.

Thus air may be regarded as having extremely high specific resistance, but its disruptive strength is low.

In the case of materials to be employed in high voltage machines, this property is of greater importance than the one first mentioned. In some cases other electrical properties (such as permittivity and dielectric hysteresis) may be important.

(3) Considerable mechanical strength both in tension and compression.

Of very great importance, but most insulating materials are defective in these respects, especially as regards strength when subjected to tension.

Hence when they have to resist mechanical stresses, they are usually arranged to be in compression. This is particularly noticeable in insulators used on overhead equipment of tramways.

(4) Inertness and permanence.

It is very desirable that insulating materials should not lose their nature in the course of time either through contact with air or other material, or through internal changes. Many substances used are poor in this respect, notably ebonite and vulcanised rubber, which are liable

to oxidise and perish by prolonged exposure to moist air and light.

(5) Impermeability to moisture.

Many otherwise useful materials readily take up moisture from the atmosphere, thereby becoming semi-conductors. Cotton and vulcanised fibre are very hygroscopic, and the poorer qualities of porcelain depend largely upon the glaze, and its ability to exclude moisture, for the preservation of their insulating properties.

Such substances will, as a rule, have both their insulation resistance and disruptive strength lowered by the presence of moisture.

With glazed porcelain or glass trouble sometimes arises owing to the deposition of a film of moisture which allows surface leakage to take place.

(6) High melting point.

This becomes of especial importance in practice in connection with materials used for cable insulation. If the melting point of the material used is too low, heat from outside, or generated in the cable, may soften the insulation and allow the conductors to move. This would be disastrous in two- or three-core cables.

(7) Incombustibility.

Many cases occur where insulating materials come into contact with arcs or heated metal as, for example, in commutators, and in jackets of enclosed fuses, and in such situations this property is obviously of the first importance.

The most common insulating materials and their uses are briefly described below.

A. Fibrous materials.

Cotton is largely used for the insulation of dynamo wires; it is very hygroscopic, and after thorough drying should be protected by varnish.

Paper is used for the insulation of high tension cables; it is then usually impregnated with a preservative compound and lead sheathed to prevent access of moisture. Similar fibrous materials are used in the form of *press-spahn*, etc., for slot insulation in electrical machines.

Vulcanised fibre is made from wood-fibre and is largely used for fuse jackets, handles, and insulating bushes; it is hygroscopic and readily carbonises and smoulders.

B. Mineral materials.

Marble and *slate*, being fireproof and readily worked, are used for low tension switch-boards and for operating panels of high tension boards, also for switch-bases. Marble should be polished on the front and varnished on the back to diminish the accumulation of dirt. Slate should be free from metallic veins and either enamelled or impregnated with oil or wax to prevent access of moisture.

Porcelain is used for switch-bases and for high tension insulators. When of good quality it is close grained and well vitrified throughout, and hence practically non-absorbent.

Asbestos is largely used for the insulation of fireproof cables and wires.

Mica is an insulating material, unique as regards flexibility and resistance to high temperatures; its chief use is for inter-segmental insulation in commutators.

Micanite is constructed by sticking together thin sheets of mica by means of as small a quantity as possible of some cement which softens when heated. On account of this property of the cement micanite may be moulded when warm and is largely used for end ring insulation in commutators and for slot insulation in generators and motors.

Bitumen (solid) has been used for cable insulation; it is very inert, but softens at too low a temperature. A product of bitumen known as *vulcanised bitumen* has largely replaced it in use for cable work; this substance is inert, does not soften at so low a temperature as pure bitumen, and is less inflammable than the majority of substances used for the above purpose.

C. Gummy materials.

Rubber (see page 293). *Vulcanised rubber* (see page 293).

Ebonite is a vulcanised rubber having a high proportion of sulphur; it has very good insulating properties, but when exposed to light and moist air it decomposes, producing an acid-conducting film which allows surface leakage to take place.

D. Synthetic materials.

Bakelite.—In recent years synthetic insulating materials have been developed, perhaps the best known

being bakelite. This is a synthetic resinous body, which, we are informed by Messrs. Attwater and Sons who manufacture the material, is prepared by causing a reaction to take place between a phenol and an aldehyde, usually formaldehyde, in the course of which water is split off. The resulting products may vary from a viscous sticky liquid to a solid transparent resinoid. The outstanding property of these synthetic resins, which differentiates them from naturally occurring fossilised resins, is that under the influence of heat they become infusible and insoluble and practically inert to chemical re-agents. In their initial state they are soluble and may be employed in varnishes for coating and impregnation work.

If the solid resinoid is powdered and mixed with suitable fillers and colouring material, it may be used for making mouldings under the influence of heat. The resulting product (bakelite) is unaffected by further application of heat, possesses good insulating properties and is capable of taking a high polish. It has become a very important insulating material.

Influence of temperature.

Increase in temperature as a general rule enormously lowers the insulation resistance and also the disruptive strength. The direct effect of temperature may, however, be masked by other indirect actions; thus it has been pointed out that the insulation resistance of unvarnished cotton at first rises with increase of temperature, due to moisture being driven out, and then commences to fall again, ultimately reaching a very low value due to carbonisation. For the same reason, the insulation resistance of a newly erected generator often improves when warmed up during the first run.

Influence of vibration.

In many situations insulating material is subject to excessive vibration, as for example in the field coils of car motors. In such cases ordinary insulating material is quickly abraded and short circuits ensue. Good results in cases of this nature have been obtained by using cotton-covered wires and interspacing with a putty-like material which dries and hardens under the influence of heat, thus leaving the field coil a solid mass well fitted to withstand vibration. Bakelite products are used for a similar purpose.

APPENDIX IV TO CHAPTER VIII

IGNITION MAGNETOS

The development of fast-running petrol engines in connection with motor-cars first created the demand for a reliable system of electric ignition, and the advent of the aeroplane greatly increased the stringency of the conditions to be satisfied. This demand has been met by systems making use of accumulators and by systems making use of magnetos. For aeroplane work magnetos are universally used, but for motor-cars, while magnetos are chiefly used in this country, accumulator systems are much in vogue in America. As regards magnetos, the result has been the evolution of a working type, simple enough in principle, but highly specialised in detail. The form described on page 126 is unsuitable because the E.M.F. cannot easily be made great enough to produce a suitable spark, and in the first attempts, made about the beginning of the present century, the magneto was merely used to excite the primary of an ordinary induction coil. The next step was to combine the two devices in one frame, and the armature of a modern rotating armature type of magneto may be regarded as an induction coil, with primary and secondary windings, which can dispense with a battery because its primary current is produced by the revolution of conductors in a magnetic field.

Before the war the Germans (notably Messrs. Bosche) possessed almost a monopoly of the magneto trade, and also of the manufacture of suitable permanent magnets for magnetos and for other purposes. Since then both industries have been successfully developed in this country. The British Thomson-Houston Co., of Rugby (in conjunction with some dozen other firms), has taken a prominent part in this enterprise, and our description is based upon information supplied by that firm and from very useful articles on the magneto written by Mr. A. P. Young, who is a member of the B.T.H. staff.

Let us suppose that the armature of a machine similar to that shown in Figure 83 is wound with two windings of few and many turns respectively (the ratio of the turns is about 1 : 50). These windings are carefully insulated from each other and from the core, and then they are connected end to end, and the outer end of the winding with fewer turns is connected to the core, the general scheme of connections being shown in Figure 129.

It will be seen that the low-tension primary, which represents an ordinary armature winding, is short-circuited by the contact A. This contact is operated by a bell crank lever attached to the armature and rotating with it, and at certain points in its revolution this lever comes into contact with fixed cams which cause it to move, thereby opening the contact A for a short period. A condenser B is also provided, which may be regarded equally correctly either as a shunt to the contact breaker or to the primary winding.

Suppose the armature to rotate with both windings on open

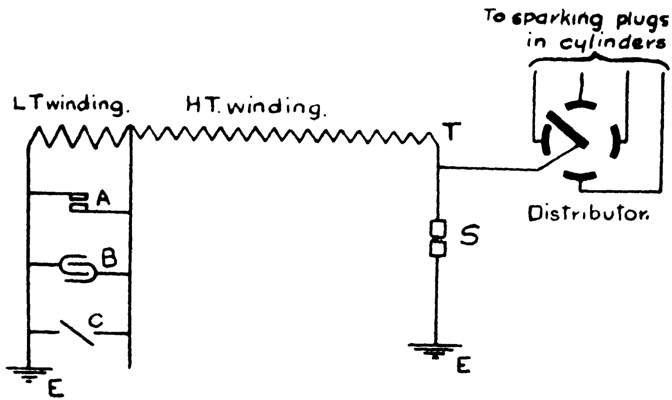


FIG. 129.

circuit, so that an E.M.F. is induced in each winding, although no current flows. Under these conditions, in a certain instance the primary E.M.F. was 27·2 volts, and as the winding ratio is 1 : 50, the secondary E.M.F. was about 1400 volts, the speed being 1000 revolutions per minute.

Experiment shows that the secondary voltage is almost directly proportional to the speed up to about 500 revolutions per minute, but increases less rapidly at higher speeds. At 2000 revolutions per minute it was about 2040 volts. Such a voltage will give a feeble spark, but it is much too low to be of any use. It represents the effective limit of normal magneto action. Now suppose the primary to be short-circuited, the secondary remaining on open circuit as before. Evidently an induced alternating current will flow in the primary, and experiment shows that this current varies very little in strength throughout a wide range of speed.

For instance, at 250 revolutions per minute the maximum value was 3·4 amperes, and at 2000 revolutions per minute it had only increased to 4·6 amperes. This is a very important fact, for the speed of running may vary very much in practice. Such a current is quite analogous to the primary current of an induction coil, and if we break the primary circuit at the instant it has attained its maximum value, the rapid disappearance of the linked magnetic flux will create a large induced E.M.F. in the secondary. Tests made on the British Thomson-Houston Co.'s type W machine show that its effective sparking value is about 10,000 volts, even at low speeds, and that the instantaneous maximum value is considerably greater. This E.M.F. produces a very satisfactory ignition spark.

The instant at which the primary circuit should be broken will be apparent from Figure 130, for we have already shown that in this position of the armature the induced current due to revolution is at a maximum. As a matter of fact, owing to self-induction, the maximum current value is not reached until the armature has passed slightly beyond the position shown, and the timing lever is so arranged that the break occurs after a further rotation of from 8° to 29°, according to the adjustment.

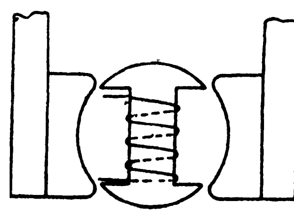


FIG. 130.

It is unnecessary to discuss the function of the condenser, for that has already been dealt with on page 105. But it must be remembered that its presence is of vital importance, and that were it to be removed the magneto would be useless commercially. The ignition spark would be ineffective, and the contact breaker would be speedily ruined by excessive sparking.

It will be seen from the above description that sufficient voltage to produce a good spark is available between the frame of the machine (i.e. the earth) and the well-insulated extremity (T, Figure 129) of the secondary or high-tension winding. This end of the H.T. (high-tension) winding is connected to a rotating brush in the distributor, and as this brush rotates it connects up to the insulated side of the sparking plug in each cylinder in turn, the sparks taking place between this contact in the plug and another metallic point which is connected to the metal of the cylinder (i.e. to earth).

Figure 129 represents the wiring for a four-cylinder engine, which requires two sparks per revolution. As the magneto gives

two sparks per revolution, it is clear that this must be geared to run at engine speed, while the H.T. distributing brush will require to be run at half engine speed. It is, of course, necessary that the

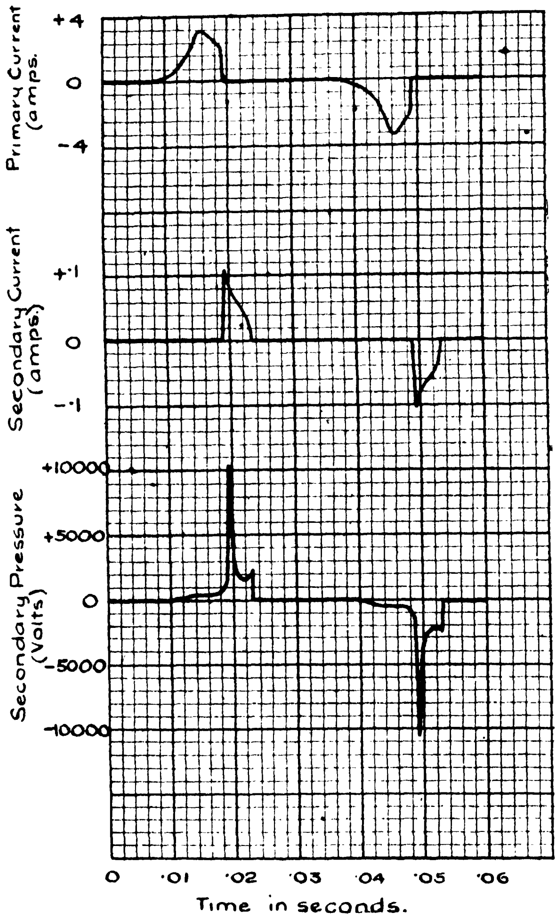


FIG. 131.

brush contacts be correctly synchronised with the motion of the armature of the magneto and with the main crank shaft, and to ensure this a positive spur-wheel drive is used.

If the sparking distance is too long (which may be due to the sparking points of the plug being too far apart, or perhaps to a H.T. lead coming off), there is the danger that the voltage between the end of the H.T. winding and the earth may reach a value sufficiently high to puncture the insulation of the machine. To avoid trouble from this cause a safety spark gap S is often provided, in parallel with the cylinder spark gaps. Here the gap is made great enough not to interfere with the normal action of the machine, and at the same time affording a path when required to safeguard the insulation.

If it be desired to stop the sparking while running the switch C is closed.

Typical curves illustrating the variation of current and voltage in the primary and secondary during 1 revolution are given in Figure 131. They are taken from oscillograph records obtained by one of the authors. These are practically self-explanatory, and the only point worthy of special mention is that the instant of break of the primary current may be varied somewhat by slightly moving the fixed cam operating the primary contact breaker, thus advancing or retarding the spark with respect to the position of the piston in the engine cylinder. Thus when starting the spark can be retarded with advantage, and when running at full speed it may be slightly advanced.

Although the type of magneto described above has been widely used, and on the whole has given satisfactory results, there are certain objections to its construction and operation, which may be summarised as follows:

1. The armature is not as a rule built up on a straight through shaft (chiefly due to the insertion of the condenser in the moving armature).

2. The space available in the armature for the condenser is very limited, and in some makes the use of a larger condenser would be an improvement.

3. The H.T. winding is moving, and is thus more difficult to insulate satisfactorily than if fixed.

4. Only two sparks per revolution can be obtained.

5. Owing to the design of the primary contact breaker, trouble may occur at high speeds due to the effect of centrifugal force.

6. A number of sliding contacts are necessary.

These objections have led to the production of the **Inductor** types of magnetos, in which the various difficulties are more or less overcome. Two distinct forms have been used: (*a*) the **Sleeve** type, (*b*) the **Polar** type.

Sleeve Type.—The principle of this will be evident from Figure 132. The armature on which the two windings are placed

is *permanently fixed* in the position shown, and the only moving parts are the soft iron inductors DD, which rotate between the pole pieces and the armature core. It will be noticed that there are four positions in each revolution for which the flux through the armature is changing rapidly (two when it is rising and two when it is falling in strength), and these positions correspond to the instants of maximum induced voltage in the primary. Hence by opening a suitable contact (not necessarily of the same design as that already described), **four** sparks per revolution may be obtained, separated by equal time intervals.

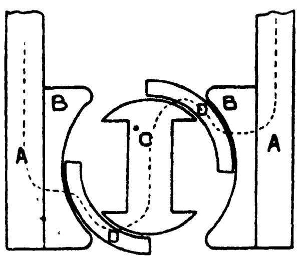


FIG. 132.

The chief objection to this type of inductor magneto lies in the purely mechanical difficulties of mounting the fixed armature core and the moving inductors.

Polar Type.—In this type the design is so widely modified that all resemblance to the original magneto practically disappears. The two windings shown as W in cross-hatched section in Figure 134, and in profile as W in Figure 133, are carried by a stationary laminated core C which is shaped very much like a horseshoe electromagnet. The underlying idea will be understood if we suppose that IN and IS, Figure 134, represent the poles of a four-pole magnet which rotates in the position shown in the figure. The magnetic flux through C then reverses its direction four times per revolution, thus giving four sparks per revolution. IN and IS are really soft-iron inductors, deriving their magnetism from a fixed steel permanent magnet PM. It should be noted that the position of the shaft with reference to the plane of this permanent magnet is at right angles to that customary in the ordinary type of machine.

Figure 133 shows the steel magnet PM, provided with soft-iron pole pieces P_1 and P_2 which are bored out to receive the inductors IN and IS, the air-gap clearance being very small to minimise the reluctance of the magnetic circuit. Each of these inductors (which are mounted upon a shaft of non-magnetic nickel steel) carries two wing-like pole pieces, interleaving with one another, as indicated in Figure 134, so that at the instant shown in the figure only the two inductors passing the core are strongly magnetised.

In consequence of the peculiar arrangement of the magnetic

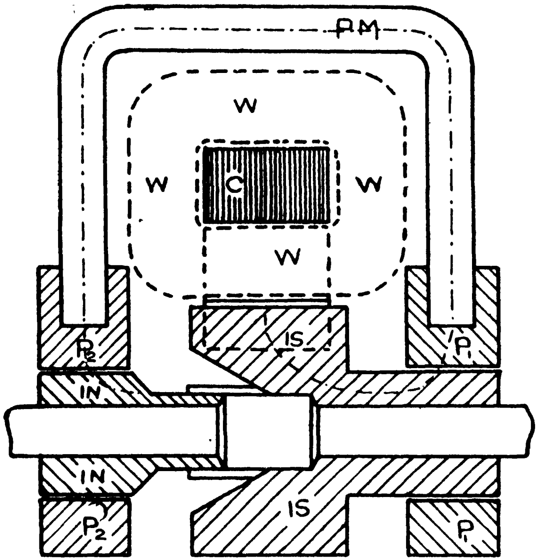


FIG. 133.

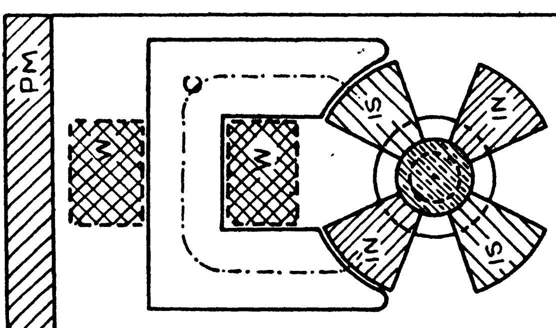


FIG. 134.

circuit it is not easy to indicate the path of the flux, but it is shown as fully as possible by the chain lines. The ball bearings (not included in the figure) are situated just outside the ends of the permanent magnet. The bell crank lever operating the contact is fixed, and a cam rotates, a modification which ensures satisfactory working at high speeds.

Most of the difficulties already outlined are surmounted in this type, and it shows signs of becoming very popular for multi-cylinder work.

CHAPTER IX

DIRECT CURRENT MOTORS

AS already explained on page 78, a motor is driven by the mechanical force exerted on a conductor carrying a current at right angles to the lines of flux in a magnetic field. It is not the only method of obtaining motion—certain toy machines act differently, by attraction of soft iron armatures for instance; but it is the only method which is of practical value and we shall confine ourselves to it.

It has also been stated that there is no essential difference in design between direct current generators and motors, and hence the diagrams and the constructive details previously given for generators apply without alteration to motors. Modifications in detail may be called for by the altered conditions of working; for instance, a motor usually has to stand more variations in load and more knocking about than a generator, and consequently should have a more robust constitution.

Consider Figure 85 (p. 128) which represents an ordinary drum or ring armature working as a generator, and for the present assume the fields to be series-wound. We know that under these conditions the force on the armature conductors tends to oppose the rotation, and must be overcome by the driving power. Now suppose we remove the driving power, but keep the same current flowing in the same direction as before in both armature and field, say by connecting them to a suitable battery. Obviously the mechanical force on the armature conductors is unaltered in direction and magnitude and the armature will evidently be driven backwards; it has become a motor. If we reverse the direction of current in either armature or field, it does not matter which, the direction of the force will be reversed and with it the direction of

rotation, but if we reverse the current on both, then the double change will leave it running in the same direction as at first.

Hence we see that if a series-wound machine is connected up correctly to work as a generator for a given direction of running, it will run in the opposite direction as a motor, whether the driving current passes through its windings in the same direction as before, or in the opposite way.

This shows that such a machine ought to work with an alternating current, and in fact it will do so readily enough without any alteration whatever, running backwards against the brushes if the latter are set for working as a dynamo. There will be much loss by eddy currents in the pole-pieces and yokes (unless they are laminated), and also trouble with sparking except at very small loads; but the principle is sound and forms the basis of the modern series motor for alternating currents which has only quite recently been developed commercially, and which appears to have a most promising future.

It also follows from what has been said above that if a given armature runs the same way both as generator and as motor, it is certain that if the armature current is in the same direction in both cases the field current is reversed, and vice versa. This means, although in this volume the fact will only be mentioned, that the "armature reactions" (see p. 170) are reversed, and that in consequence the brushes of a motor naturally require a backward lead.

Consider a motor made to run at, say, 100 volts, with a full load current of 50 amperes. Its internal resistance will be quite small, and the larger the motor the smaller it will probably be; but suppose, for example, it is 0·2 ohm, which is rather a high value.

If we put 100 volts on it, by Ohm's Law the current will be 500 amperes, and it is only supposed to carry 50; again, the current will be the same whatever work it is doing if only the ohmic resistance has to be considered. But experience shows that a motor is largely self-regulating, only taking energy from the source of supply as required by the load, and if this were not the case it would be most wasteful except when working on a fixed load. Hence there must be something else to consider besides resistance, a fact which can be

easily demonstrated by running the motor with an ammeter in circuit and varying the load. It will be found to take the greatest current when running slowest, i.e. when at rest, and that the faster it runs the smaller becomes the current.

To explain this we must now point out that the two actions studied separately for convenience as the "motor principle" and "generator principle" are as a matter of fact inextricably bound up together, so that one never comes into effective existence without the other. For as soon as we apply the generator principle to obtain a current by moving a conductor in a magnetic field there is a resistance to motion due to the motor principle, and conversely, when we apply the latter to obtain motion, as soon as the motor armature begins to rotate there is an induced E.M.F. in it due to the generator principle, which, from what has already been said about the direction of running, must evidently be in opposition to the current which drives the motor. This is called the back E.M.F. of the motor.

Let V = applied voltage, supposed constant, that is the reading a voltmeter would give if connected across the motor terminals,

E_m = back E.M.F. of motor,

R_m = resistance of motor armature circuit,

then the current through the armature is given by

$$I = \frac{V - E_m}{R_m}$$

This back E.M.F. is in no way different in nature from the armature E.M.F. already dealt with in the case of generators, and it is exactly what the machine would produce as a generator if running under similar conditions in the same field and at the same speed.

$$\therefore\ E_m\ (\textit{average}) = \frac{\textit{lines cut per conductor per revolution} \times \textit{conductors in series} \times \textit{revolutions per second}}{10^8}$$

This shows that it varies with the field strength and with the speed, being zero when the motor is at rest, hence $I = \dfrac{V}{R_m}$ in that case. The armature current decreases as the speed, and therefore E_m, increases. It has already been mentioned

that a current can only do external work by flowing against an opposing E.M.F. (see p. 66), therefore we can write :—

Power taken from source $= V \times I$ watts.

Power developed by motor $= E_m \times I$ watts.

Power wasted in copper as heat $=$ the difference $= (V - E_m) \times I$ watts,

for copper loss $= I^2 \times R_m = \left(\frac{V - E_m}{R_m}\right) \times I R_m = (V - E_m) \times I$.

It must not be assumed that power equal to $E_m \times I$ watts is actually available for external work. From this must be deducted the various losses due to eddy currents, friction of bearings and brushes, etc., and also the loss due to changes of magnetisation in the armature core (known as the "hysteresis loss"), in order to obtain the brake horse-power.

The preceding statements apply generally to all direct current motors.[1] We can now discuss their special behaviour in more detail.

SERIES-WOUND MOTOR

If a machine be connected up for running as a generator, it is evident, from what has already been said, that it will run backwards as a motor whichever way the current passes through it.

Hence for a given direction of running the field connections which are right for a generator are wrong for a motor, and vice versa. This statement is liable to be misunderstood. In the case of a motor the connections are never wrong in the sense that it refuses to work; it will always run one way or the other, but if we try to drive it as a generator in the same direction as it naturally runs as a motor, we find that it absolutely refuses to generate. This is because the small initial current due to residual magnetism passes through the fields in a direction which tends to weaken that magnetism; in order to make it "excite" as a generator, we must either run it the other way or reverse the field connections.

The turning effort or "torque" produced by the motor depends only upon the strength of the field and the strength of the armature current; in this case the armature current also passes through the field winding, so that both vary

[1] Note that in a shunt or in a compound machine the armature current is obviously slightly less than the current taken from source.

together, and the torque will be strongest when the armature current is strongest. If a constant P.D. is applied to the motor terminals, this will occur when the back E.M.F. is zero, that is, when the motor is at rest. This great starting torque is the most valuable property of a series-wound motor, and determines its general adoption for traction purposes.

An equally characteristic property of series motors is the variation of speed with load. The motor slows down under heavy loads and races dangerously at no load. This does not interfere with its usefulness for traction, but means that it is unsuitable for running machinery or tools, such as a lathe, which require to be driven at fairly constant speed in spite of sudden and frequent changes in the load.

To explain this behaviour we must consider further certain general properties of motors.

From the equation $I=\frac{V-E_m}{R_m}$ we see that when a motor runs, as it usually does run, on a constant potential circuit, the only way of altering the power VI supplied to it is to alter the current; and further, that the only way of altering the current is to alter the value of E_m. For simplicity, consider a machine in which the fields are separately excited, that is, kept at absolutely constant strength by some independent source of current. Let it be working on a certain load at a definite speed, and then suppose we increase the load, i.e. the resistance to turning. The first effect is to slow it down somewhat; this reduces the back E.M.F., and the current in consequence increases, more power being thus supplied, which tends to speed it up again. Now the important point to be grasped is, that a very trifling decrease in speed will, in the case of a motor of low internal resistance, greatly increase the power supplied, and hence the motor can adapt itself to a wide range of load by means of a very slight variation in speed. For suppose the internal resistance to be 0·2 ohm, and let the motor be running from 100 volt mains at such a speed that the back E.M.F. is 95 volts.

$$\text{Then } I=\frac{100-95}{0{\cdot}2}=25 \text{ amperes.}$$

Power supplied $= VI = 100\times25=2500$ watts.
Power developed$=E_m\, I=95\times25=2375$ watts.

Now let the load be increased until E_m drops to 90 volts, which means about 5% reduction in speed.

$$\text{Then } I = \frac{100-90}{0 \cdot 2} = 50 \text{ amperes.}$$

$$\text{Power supplied} = VI \quad = 100 \times 50 = 5000 \text{ watts.}$$
$$\text{Power developed} = E_m\, I = \ 90 \times 50 = 4500 \text{ watts.}$$

This is the power required by the new load at the new speed, and from it we see that in this case almost double the load can be taken with only 5% decrease in speed. Had we taken the internal resistance at 0·1 ohm, doubling the load would only have meant 2½% decrease in speed.

Arguing conversely, we see that the load can be reduced with an equally slight increase of speed. Only keep the field at constant strength and the motor will never race, even at no load, because a small increase in speed will diminish the current until the power taken is just sufficient to balance the various losses. Assuming an impossibly perfect machine with no losses, we see that with scarcely any change of speed E_m would become equal to V and the current would become zero, for it would then require no power to keep it in motion at no load, when it had once been run up to speed.

With the actual series motor the field is anything but constant, and if as before we suppose the load to be increased when it is running, the speed decreases and hence E_m falls; but now the consequent increase of current strengthens the fields, which tends to increase E_m again and check the increase of current. As a result the current cannot increase as much as it would do if the fields remained constant in strength and the extra supply of power derived from the mains is not so great for a given decrease in speed, so that the motor has to slow down more than before to obtain whatever extra power is required. Conversely, when the load is removed altogether the increase of speed tends to increase the back E.M.F., but the decrease in current tends to decrease it by weakening the fields, and hence the armature has to run at an enormous speed in a weak field before it can increase E_m to the value required to keep the current down to the small amount required to balance the various losses.

SHUNT-WOUND MOTOR

The first important property of this type is the fact that for a given direction of running the field connections are the same both as motor and as generator. If right for working as a generator it runs the same way as a motor, whichever direction the current passes through it. The diagrams will show why this is the case. The upper part of Figure 135 shows the machine working as a generator. Here the E.M.F originates in the armature, and the current in consequence divides at terminal A. In the lower part of the same figure the machine is connected to an external source of E.M.F. in such a way that current flows through armature in the same direction as before. But now it divides at terminal B, and hence the current is reversed in the field winding. Were it the same as before we know that the motor would run backwards; as it is, the reversal of the field reverses the direction of the force on the armature conductors and it runs forward. A change in the direction of the applied E.M.F. merely changes the direction of current in both armature and field winding, and does not affect the running.

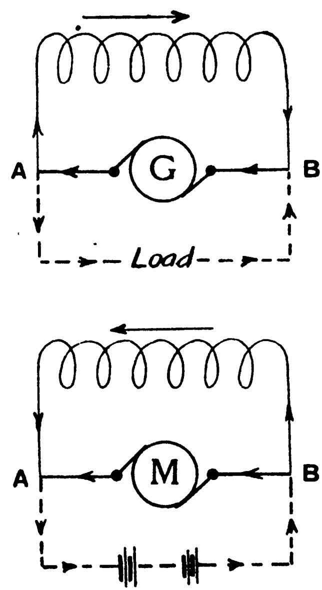


FIG. 135.

We may note in passing that a shunt-wound motor will not necessarily run with alternating currents, although the argument used for the series motor applies equally to this case. This is because the armature and fields now form two independent paths, and apart from the increased choking effect of the field winding we can no longer rely upon the current in each reaching its maximum and minimum at the same instant. Even with a strong field and a large armature

current the average force on the conductors may be very small, although the matter cannot be adequately explained here.

The next important property is the fact that a shunt-wound motor runs at nearly constant speed at all loads. It is true that it must and does slow down, but it may be by a quite small amount. This follows at once if we notice that, as V is constant, the shunt current is also constant, and hence the field remains of the same strength whatever may be the current in armature. It follows that the previous remarks about a separately excited machine apply at once without alteration.

The above statement is, however, not quite true, although the exciting ampere-turns of the field are really constant.

The study of armature reaction shows that there is a natural and inevitable tendency for an armature to demagnetise or weaken its own field by some amount proportional to the armature current, if the brushes are in the correct non-sparking position. As a result, the field strength may slightly decrease as the load on the motor increases, but this effect is in reality a useful property and not a disadvantage. For, as already pointed out, the only way of increasing the power to a constant potential motor is to diminish the back E.M.F. slightly, and so far we have considered mainly the influence of speed. But a slight reduction in field strength is an equally effective way of reducing the back E.M.F., and hence it follows that slightly weakening the field of any motor at once increases the power taken from the source, and thereby tends to make it run faster. Conversely strengthening the field makes it run slower. For these reasons the natural demagnetising effect of the armature reaction helps to keep up the speed as the load increases, and improves the regulation of a shunt-wound motor.

An obvious development of this idea is to insert a regulating resistance in the shunt circuit just as is done in the case of a shunt-wound generator. Then by suitably weakening the field as the load increases the machine may be made to run at quite constant speed at all loads, or even to increase in speed at full load.

Obviously only slight variations in field strength are implied. The force on armature conductors depends jointly on armature current and field strength, and to reduce the latter too much would be a fatal mistake. Our statement simply means that a slight decrease in field strength will increase the current to

such an extent that the product of the two is momentarily greater than before.

This type of motor cannot respond to an exceptional overload quite as well as a series-wound machine, for, in the latter case the two factors in the turning moment increase together (apart from the influence of saturation), whereas in the former it is only the armature current which increases. As a consequence, the shunt winding has been hitherto but little used for traction or other purposes where occasional excessive loads may be met with, but it is excellent when nearly constant speed between no load and full load is required.

COMPOUND-WOUND MOTOR

Compound field windings (i.e. field windings having both shunt and series coils, the two coils helping each other magnetically) are sometimes used for D.C. motors and perhaps the chief advantage to be obtained from their employment is the improvement in starting torque as compared with the starting torque of a shunt motor.

During starting the armature current is likely to be in excess of the full-load value and this current, passing round the series turns of the field will, if the magnetic circuit is not too nearly saturated at any part, give rise to a value of field strength in excess of that at normal full load and a corresponding increase in torque during the starting period will result. Compound windings are also useful when D.C. motors are used to drive fans or pumps since they will minimise the risk of overloading the motor. When a shunt motor has been running for some hours the temperature

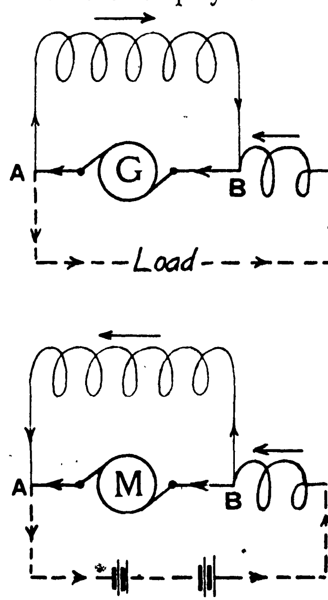


FIG. 136.

rise will have attained a considerable value and this will result, owing to the increase in field resistance if a field regulator is not employed, in an increase in speed of the machine. For loads of the nature stated the necessary power increases rapidly as the speed rises and overloading of the motor may result. If a compound-wound motor is used, the increase in current due to the increase in load will tend to maintain the strength of field and thus the increase in speed, and therefore of load, will not be so great as when a shunt motor is used. Field windings having the magnetic effect of the series turns opposed to that of the shunt turns are also occasionally used, the special advantage obtained being that the progressive weakening effect on the field of the series turns as the load increases prevents, or tends to prevent, the drop in speed which occurs when a simple shunt winding is employed. This arrangement, sometimes referred to as a differential winding, will obviously result in very poor starting torque (the armature might even tend to run the wrong way if the armature current at starting was excessive and the fuses did not blow) and for starting purposes it may sometimes be desirable to temporarily reverse the connection of the series winding. If we have a machine running as a compound generator and we wish to run it as a motor in the same direction, we may do so by retaining the same direction of current in the shunt field and reversing the direction of current in the armature circuit. This will also result, however, in a reversal of current direction in the series field and it will be necessary to reverse its connection relative to the armature. Further, if we wish to reverse the direction of running of a compound motor, we should probably do so by reversing the direction of current in the armature circuit and this will also reverse the direction of current in the series field coil. To counteract this it will be necessary to reverse the connection of the series winding relative to the armature as compared with that used in the original direction of running. If the machine is fitted with commutating poles the windings of these will also be in series with the armature but the connection of these relative to the armature should not be changed. The necessary reversal in the polarity of the commutating pole will be secured by the reversal of current in the armature circuit.

STARTERS FOR D.C. MOTORS

The equation of current through a motor, $I=\frac{V-E}{R_m}$, shows that to switch on full voltage while the motor is at rest would probably burn it out, apart from the shock of a too sudden generation of torque. The only rational way of starting up is to make the applied voltage V small at first and to increase it gradually as the speed increases. This is most conveniently done by inserting a suitable resistance and cutting it out by successive steps. Waste of energy in the process is unavoidable, and when starting and stopping is of frequent occurrence, as in traction work, this becomes of considerable importance. The material used for the resistance itself may be of iron wire, or some of the modern high resistance alloys, such as " Eureka." For heavy work cheap alloys cast in the form of grids may be used. The higher its resistivity, the shorter will be the length and the greater the section of the conductor required, and the additional stiffness thus obtained is an advantage. Increased resistivity may or may not necessitate increased bulk of material, according to the working conditions.

For series motors it is only necessary to put such a resistance in the main circuit, but most modern starting switches have in addition a device which will automatically open the circuit should the line current fail, for evidently if a number of motors are in use in a factory, and the supply of current is interrupted for a short time, on re-establishing the supply each would amount to a nearly dead short across the line if left in circuit. In addition there may be an overload cut out to switch off the motor if it is pulled up by some accident to the machinery it is driving, or this contingency may be guarded against by a fuse.

A simple form of starting switch for a series motor is shown diagrammatically in Figure 137. The switch handle has a piece of soft iron attached to it, and is held over, against the opposing pull of a spring, by the attraction of an electromagnet A, excited by the load current or a portion of it. If the current fails the handle flies back into the " off " position, and the motor can only be restarted by again switching on the resistance R.

The details are more fully shown in the subsequent figure of a shunt-motor switch.

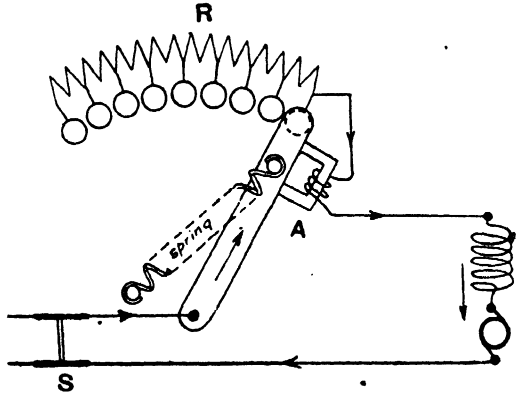


FIG. 137.

STARTING RESISTANCE FOR SHUNT-WOUND MOTOR

When a student proceeds to use a shunt motor for the first time he very frequently puts a resistance in series with it exactly as he has been accustomed to do in the case of a series motor (as at A in Figure 138), and then he finds to his surprise that it does not start, or only with difficulty, although the full load current may be passing through armature. Obviously this is because the field is very weak; for suppose it is a 220-volt motor with an internal resistance of 0·5 ohm, and we send, say, 20 amperes through it whilst the armature is at rest. The P.D. across the armature is then $20 \times 0{\cdot}5 = 10$ volts, and this is the voltage exciting the shunt coil, although it ought to have 220 volts. What is wanted at starting is the strongest possible field, and then quite a small current will develop considerable torque. The starting resistance is therefore in the wrong place. It is not required to protect the field, and should be used to regulate the volts on the armature after the former is fully excited—the correct arrangement being shown at B in Figure 138. Hence we deduce the first property of a well-designed starting switch. It must fully excite the fields on the first contact.

Again, it is apparent from Figure 138 that if the shunt current fails for any reason—say a break or a bad contact in the fine wire winding—the field disappears and with it the back E.M.F., leaving the armature as an almost dead short across the mains. Some protecting device is therefore required to open the circuit in such a contingency. These are additional requirements peculiar to the shunt winding, and we need, as before, the cut-out action in case of failure of line current and in case of excessive load.

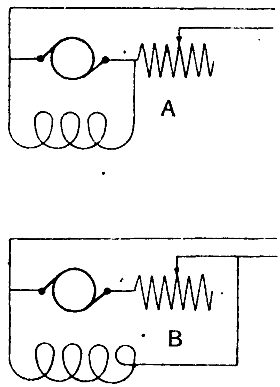


FIG. 138.

Figure 139 shows how these conditions are fulfilled in practice. As before, the switch handle is held over by the electro-magnet A against the pull of a spring, and the connections are such that on the first contact the field winding is in circuit directly across the mains, and therefore, fully excited, its current also passing through the coils of A. This path is from one of the mains M to the terminal T_1, then through a few turns of thick wire wound on the overload cut-out C and into D, which is a metal bar permanently in contact with the connecting piece on the switch handle. When the latter is moved into the first position D is connected to the stud R_1, and the path continues through the wire W, around the coils of A to the terminal T_3, and then through the shunt winding and back to the other main M_1. At the same time there is another closed path from R_1, through the whole starting resistance to the terminal T_2, and thence through the armature and back to M_1.

At the successive contacts this is gradually cut out of the armature circuit, and at the same time cut in to the shunt circuit. This does not appreciably affect the shunt current, because the whole starting resistance is quite small compared with the high resistance of the field winding, and what slight effect there is of the kind tends, as we have seen, to keep up the speed, but the great advantage derived from this method of connection is due to the fact that the shunt

circuit is not opened on switching off, a closed path remains through the armature and starting resistance. This is of great importance, for if it were opened a very high voltage would momentarily be induced in the field coils which would be very liable to break down the insulation of the field circuit. With the arrangement shown, a failure of line voltage does not immediately result in a stoppage of field current, which, for

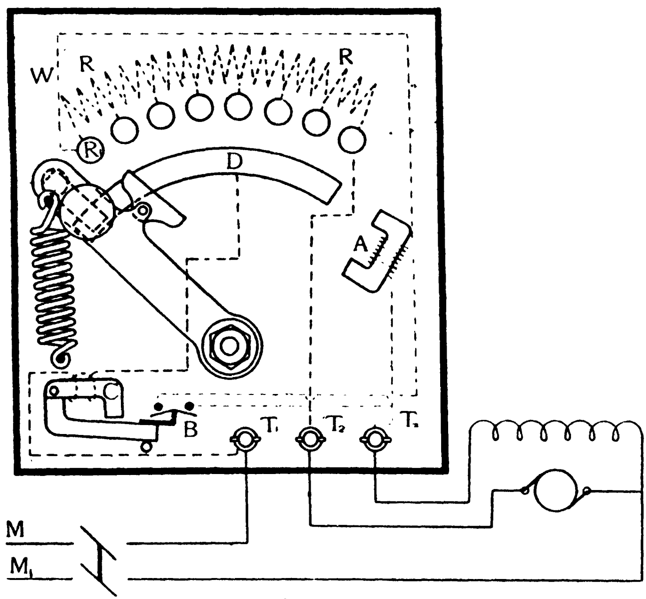


FIG. 139.

the time being, is supplied from the armature of the motor owing to the induced E.M.F. As the motor slows down this back E.M.F. gradually falls and thus the field current is only gradually reduced and the risk of the production of any high voltage due to self-induction is obviated. The use of the no-volt coil A, ensures that failure of the field current while the motor is running results in the flying back of the handle and the same result also ultimately occurs should the line voltage fail.

portional to time) is plotted as abscissa. The graph shown this Figure represents the changes taking place in the E.M.F. in one revolution of the coil and corresponds to one cycle. The number of such cycles taking place per second (in the case under consideration this will be equal to the number of revolutions which the coil makes per second) is termed the frequency of the alternating voltage. In actual

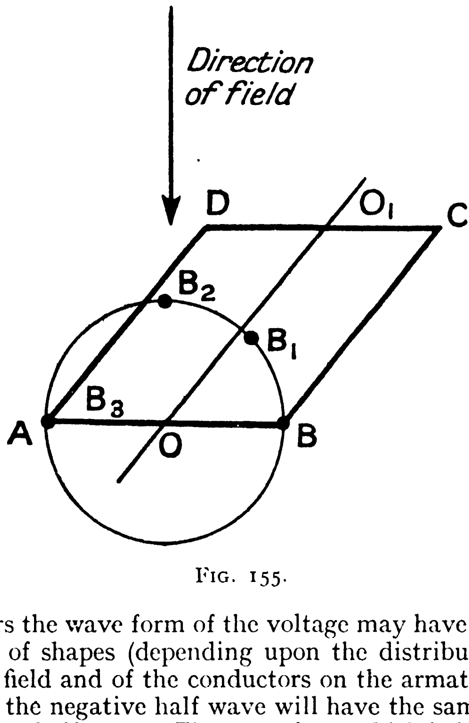


FIG. 155.

alternators the wave form of the voltage may have any one of a variety of shapes (depending upon the distribution of the magnetic field and of the conductors on the armature) but in each case the negative half wave will have the same shape as the positive half wave. The wave form which is looked upon as ideal for most purposes is known as a sine or sinusoidal wave, and it is such that, at any instant, the ordinate of the wave is proportional to the sine of the abscissa. This is the shape of the wave obtained in our simple example, and in this case the voltage generated at any instant is proportional to the sine of the angle of rotation of the coil from its initial position.

EXPRESSION OF MAGNITUDE OF AN ALTERNATING VOLTAGE

An important point arises as to how we shall express the magnitude of a voltage of this nature. It will clearly be convenient that a direct voltage of any amount should be equivalent, from the heating and power points of view, to an alternating voltage expressed by the same figure. In order that this may be the case it is necessary that the average value of the square of the instantaneous voltage, taken over a half cycle or any number of half cycles, should have the same value as the square of the equivalent direct voltage (since

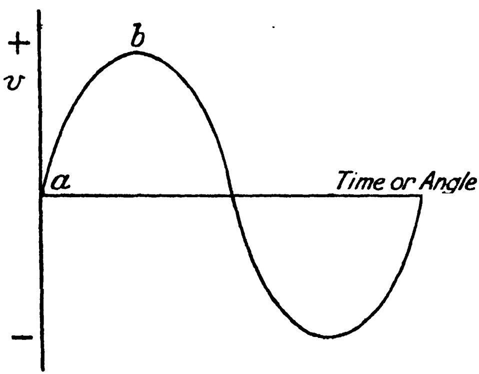


FIG. 156.

heating varies as the square of the voltage). Thus, when we speak of an alternating voltage of 100, we do not mean one whose maximum value is 100 but one whose square root of mean square value (taken over half a cycle) is 100. This is known as the R.M.S. (root-mean-square) or effective value of the voltage. As a matter of fact, if the voltage wave is of sine shape, the maximum value is 1·414 times the R.M.S. value and the average value is 0·636 of the maximum value. The points mentioned above in regard to alternating voltages also apply to alternating currents, and it is to be noted that ammeters and voltmeters for use on alternating current circuits are constructed and calibrated so as to read the R.M.S. values of the quantity concerned.

CURRENTS SENT BY ALTERNATING VOLTAGES

(*a*) *Through Circuits having Resistance only.*—In a purely resistive circuit the voltage will, at any instant, send a current whose value can be determined by a simple application of Ohm's Law. The wave of current will pass through its maximum and zero values at the same instants as the voltage wave, and the two are said to be " in phase " with each other

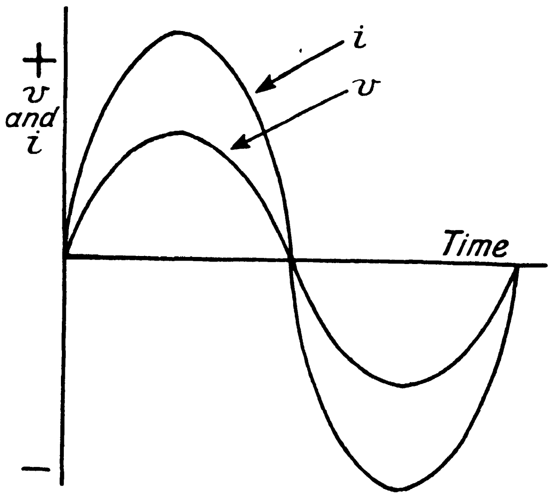


FIG. 157.

(i.e. in step with each other), the state of affairs being shown in Figure 157. In such cases we may, if R.M.S. values of voltage and current are used, employ the ordinary law $I = \frac{V}{R}$.

(*b*) *Through Circuits having Self Inductance only.*—Inductive circuits are those in which magnetic lines (linking with the current) are produced when current flows through the circuit, and we have already seen that in such circuits induced E.M.Fs. are produced whenever the current is changing in magnitude. The unit of self inductance is termed the henry, and a circuit possesses a self inductance of one henry

if it is such that a rate of change of current within it of one ampere per second produces an induced E.M.F. of one volt. The magnitude of the induced E.M.F. at any instant in an inductive circuit is given by the expression: Induced E.M.F. = – Self Inductance in henries × rate of change of current in amperes per second, the negative sign being introduced because when current is rising in the circuit the induced E.M.F. is in the opposite direction to the current.

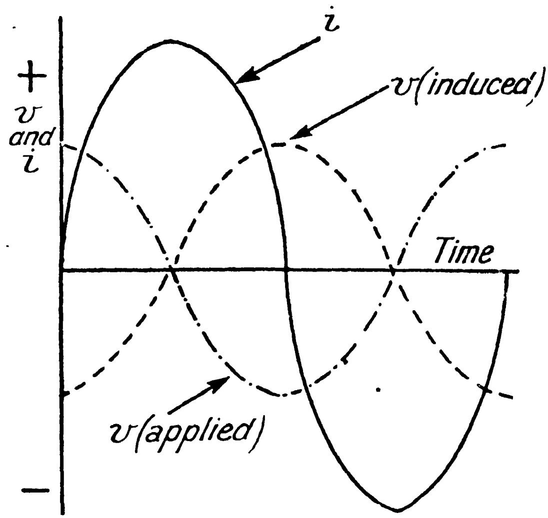


FIG. 158.

In Figure 158 the continuous line represents the current wave in an inductive circuit, and the induced voltage at any instant will be proportional to the rate of change (rise or fall) of current at that instant measured in amperes per second. This wave (the negative sign be duly allowed for) is shown by the dotted line in the Figure. The applied voltage needed to send the current must balance the induced E.M.F., and, at any instant, will be equal in magnitude to the induced voltage but will be in the opposite direction. It is shown by the chain line in the Figure.

It will be noticed in the diagram that the applied voltage

and the current do not pass through the same parts of their cycles simultaneously, and they are said to be " out of phase." As a matter of fact it will be seen that the current passes through its maximum value when the voltage is passing through its zero value and vice versa, and the two quantities are said to differ in phase by a quarter of a cycle (or 90°). An examination of the Figure will also show that the current passes through each part of its cycle at a later period than the applied voltage, and it is said to be lagging with regard to the voltage. Alternatively, the voltage may be said to be leading the current. It is not readily possible, or necessary, in an elementary book, to prove the law connecting the R.M.S. magnitudes of current and voltage with the self inductance of the circuit, but the connection is given by

$$I = \frac{V}{2\pi f L} = \frac{V}{\omega L}$$

where f is the frequency of the voltage and L the self inductance of the circuit. The term $2\pi f L$ or ωL (ω is the Greek letter omega) is termed the reactance of the circuit and is expressed in ohms. It should perhaps be stated that, in alternating current formulæ, capital letters used as symbols for current or voltage are usually used to indicate the R.M.S. values of the quantities concerned.

(*c*) *Through Circuits having both Resistance and Self Inductance.*—It is seldom that circuits are encountered which may be regarded as purely inductive, more generally they contain resistance in addition to inductance. The state of affairs under these circumstances is illustrated in Figure 159. We may look upon the applied voltage as being made up of two parts. (1). A voltage needed to drive the current through the resistance, this is shown in the diagram by the dotted line and is in phase with the current. Its value at any instant is given by the expression $v = Ri$ (the small letters indicating the values of the current and voltage at a particular instant), and its R.M.S. value is given by the expression $V = RI$, where I is the R.M.S. value of the current. (2). A voltage to send the current through the self inductance of the circuit, this voltage will be 90° (a quarter of a cycle) in front of the current and is indicated by the chain line in the Figure. The magnitude of this voltage will be given at any instant by L × rate

of change of current in amperes per second, and its R.M.S. value by the expression ωLI.

The total applied voltage will be the sum of the two and, so long as we deal with instantaneous values, it will be the algebraic sum as shown by the curve composed of small dots. We can see from the diagram that if we deal with R.M.S. values (or maximum values) the total voltage will not be the algebraic sum of the two components because they do not attain their maximum values at the same instant. It is, in

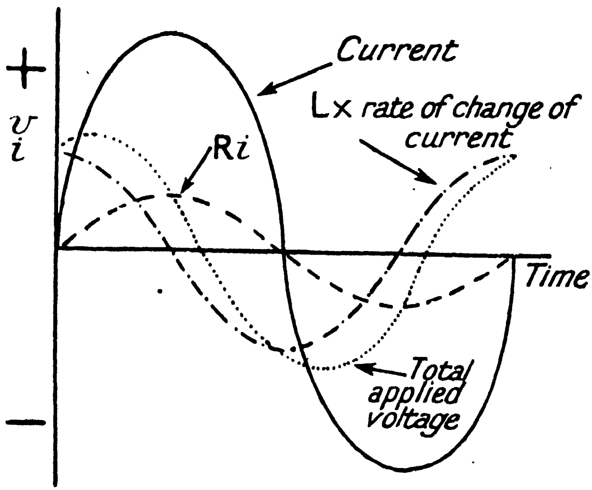


FIG. 159.

fact, what is called the vectoral sum which is needed, and it should be noted that when voltages or currents are added vectorally, not only are the magnitudes of the quantities taken into account but also their relative phases. This particular method of addition must always be employed when dealing with R.M.S. values of currents or voltages, and since it is of such importance it is desirable to study the matter at some length. Hitherto we have represented currents and voltages by what we may term wave diagrams, but other methods of representation are available, one being a graphical method using the lengths of lines to represent the magnitudes

of the quantities and the relative angular positions of the lines to represent the relative phases of the quantities.

In Figure 160 consider the line OB, which is supposed to rotate in an anti-clockwise direction round the end O, and let the time taken to make one revolution be the same as the time taken by the alternating quantity to perform one cycle. In our diagram we cannot of course show the line actually rotating, we can only show it in its position at a particular instant. If we show the line in the position OB we usually have in mind that the alternating quantity concerned is passing through its zero value rising positively (corresponding to the instant "a" in Figure 156). If we show the line in the position OB_1, we have in mind that the quantity is passing through its maximum positive value (corresponding to the instant "b" in Figure 156). The whole range of possible positions of the line (extending over 360°) can be looked on as representing all possible phases of one complete cycle.

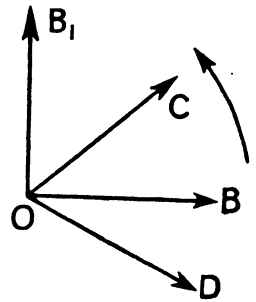


FIG. 160.

Now consider the line OC, we imagine this line as rotating at the same rate as the line OB, but it will be clear that it represents a quantity (current or voltage) which passes through each part of its cycle in advance of the quantity represented by the line OB, in other words it represents a quantity which is leading OB. Similarly, the line OD represents a quantity which is passing through each part of its cycle after the quantity represented by OB, or in other words is lagging with respect to OB. Looking upon one cycle (corresponding to one complete revolution of the coil referred to at the commencement of the chapter) as being represented by 360°, we see that two lines with an angle $\theta°$ between them may be used to represent two alternating quantities having a phase difference of $\theta°$. In a diagram of this nature, called a vector diagram, the lengths of the lines will usually represent R.M.S. values, though occasionally they may be used to represent maximum values of the quantities. Oftentimes the salient points of a problem can be more clearly and simply brought out by a

vector diagram than by a wave diagram, and the flow of current through an inductive resistance is a case in point. In Figure 161, OI represents the current flowing through the inductive circuit, while OB represents the voltage needed to send the current through the resistance of the circuit (its magnitude is IR) and is shown in phase with the current. The line OD represents the voltage needed to send the current through the self inductance of the circuit (its magnitude is ωLI) and it is shown 90° ahead of the current. The vectoral sum of the two component voltages is shown by OE and, though space does not permit of a complete discussion of the matter, it is found by completing the parallelogram, of which OB and OD are the sides, and drawing the diagonal. The process is the same as is used in finding the resultant of two forces or two velocities in elementary mechanics. Note that OB, OD, and OE represent the respective voltages to scale and, since the parallelogram is in this case a rectangle, we have

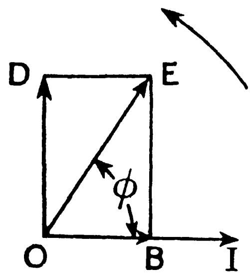


FIG. 161.

Total applied voltage $= \sqrt{(\omega LI)^2 + (RI)^2} = I\sqrt{\omega^2L^2 + R^2}$, or

$$I = \frac{V}{\sqrt{\omega^2L^2 + R^2}}.$$

We can deduce from the diagram that the angle by which the current lags behind the total applied voltage depends upon the relative values of the resistance (R) and the reactance (ωL), and a small knowledge of trigonometry enables us to see that $\tan \phi = \frac{\omega L}{R}$. The quantity $\sqrt{\omega^2L^2 + R^2}$ is termed the impedance of the circuit and is expressed in ohms.

The law given above for determining the magnitude of the current flowing in circuits possessing resistance and self inductance may be applied to alternating current circuits much in the same way as we have already applied Ohm's Law to direct current circuits in Chapter III. It should be noted

that it possesses a similar flexibility, and may be applied to an entire circuit or to a portion of a circuit, due care being taken to use the constants appropriate to the portion of the circuit concerned.

Example.—A coil having a resistance of 4 ohms and a self inductance of 0·03 henry is connected in series with a resistance of 6 ohms. If a voltage of 100 at 50 cycles per second is applied to the combination, determine the current flowing and the voltage across each part of the circuit.

Applying the law found above to the complete circuit we have

$$I = \frac{V}{\sqrt{\omega^2L^2+R^2}} = \frac{100}{\sqrt{(2\times 3{\cdot}14\times 50\times 0{\cdot}03)^2+(4+6)^2}} = \frac{100}{\sqrt{9{\cdot}42^2+10^2}}$$

$$= \frac{100}{\sqrt{188{\cdot}7}} = \frac{100}{13{\cdot}73} = 7{\cdot}28 \text{ amperes.}$$

This current will lag behind the total applied voltage by an angle whose tangent is $\frac{9{\cdot}42}{10} = 0{\cdot}942$. The angle is $43{\cdot}3°$.

The voltage across the pure resistance will be $RI = 6\times 7{\cdot}28 = 43{\cdot}68$ volts, and the voltage across the coil will be $I\times\sqrt{\omega^2L^2+R^2}$ $= 7{\cdot}28\sqrt{9{\cdot}42^2+4^2} = 7{\cdot}28\sqrt{104{\cdot}7} = 7{\cdot}28\times 10{\cdot}23 = 74{\cdot}5$ volts.

The phase angle between the current and the voltage across the coil possessing self inductance and resistance will be such that the tangent of the angle will be $\frac{9{\cdot}42}{4} = 2{\cdot}355$, and the angle is $67°$. All the currents and voltages in the above calculation are R.M.S. values, and it should be noted that the arithmetic sum of the voltages across the two components of the circuit is greater than the applied voltage. This is due to the fact that the two component voltages are not in phase with each other.

A vector diagram showing the current and several voltages is given in Figure 162. OA represents the current (which is the same in all parts of the circuit),

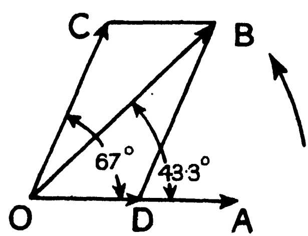


FIG. 162.

OB represents the total voltage, OC represents the voltage across the coil, and OD represents the voltage across the added resistance.

It is important to realise that in a choking coil (i.e. a coil having considerable self inductance and very little resistance) we have a means of cutting down the current in an alternating current circuit, and it may be employed for this purpose in preference to the use of a resistance. The use of a choking coil as a substitute for a resistance has the advantage that it involves little loss of power.

Example.—An arc lamp (which for the purpose of this calculation may be regarded as a non-inductive resistance) requires 10 amperes at a voltage of 60. If it is to be run off 100 volt mains at 50 cycles per second, what self inductance should be placed in series with the lamp in order that it may receive correct values of voltage and current ?

Dealing first with the circuit as a whole we have

$$I = \frac{V}{\sqrt{\omega^2 L^2 + R^2}} \text{ or } \omega^2 L^2 + R^2 = \frac{V^2}{I^2}.$$

Now the resistance of the lamp is $\frac{60}{10} = 6$ ohms, therefore

$$\omega^2 L^2 = \frac{V^2}{I^2} - R^2 = \frac{100^2}{10^2} - 6^2 = 64$$

or ωL = reactance of the choker = 8 ohms.

The self inductance of the choker $= \frac{\text{Reactance}}{\omega} = \frac{8}{2 \times 3{\cdot}14 \times 50}$ $= 0{\cdot}02547$ henry.

Note that if the frequency of the supply had been 100 c.p.s. instead of 50 c.p.s., the value of the necessary reactance would have been unaltered. The inductance need to give this reactance would have been halved.

(*d*) *Through Circuits Possessing Capacitance.*—When we have two conductors (one of which may be earth connected) separated by a layer of insulating material, as, for example, the two cores of a two-core cable, and we apply a steady difference of potential between them as indicated in Figure 163, a charge flows into the metal A (due to the passage of a small current for a short time) until the voltage between the conductors is equal to the P.D. of the battery.

Incidentally it may be mentioned that an equal quantity

of electricity flows from the metal B into the cell. If the applied voltage is steady, the current is of a momentary nature only, and, when the necessary displacement of electricity has occurred, the current ceases. In such circumstances we say that capacitance exists between A and B. The unit of capacitance is termed the farad, and is the capacitance between A and B when the dimensions and arrangements are such that one coulomb of electricity is required to flow into the metal A to produce a difference of potential of one volt between A and B. The farad is too large a unit for most practical purposes, and the microfarad ($\frac{1}{1000000}$ farad) is commonly used when stating the magnitudes of capacitances.

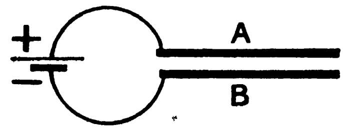


FIG. 163.

When the voltage between A and B is steady, no matter how high it may be, no current flows into or out of the conductors, but when the voltage between A and B is changing a current flows, its magnitude being given at any instant by the expression

$$i = C \times \text{Rate of change of voltage (volts per second)}$$

C being the capacitance in farads.

If the voltage applied to the capacitance is of an alternating nature, it will either be rising or falling at practically every instant and the above formula may still be applied for the purpose of finding instantaneous values of the current.

In Figure 164 the continuous line represents the wave of applied voltage and the dotted line represents the resulting wave of current which is seen to be of an alternating nature (as a matter of fact if the applied voltage is sinusoidal, the current will also be sinusoidal) and leads the voltage wave by a quarter of a period. If an ammeter, suitable for indicating alternating currents, is placed in the circuit, it will read the current in just the same way as it would if placed in a resistive circuit despite the fact that in the circuit under consideration there is not a complete metallic path. A current flowing through a capacitance in this way will have just the same properties in other parts of the circuit as a current flowing in a closed metallic path. Between each pair of cores of a

multi-cored cable capacitance exists and such a cable takes current from a source of alternating supply even if no load be connected between the cores. In large systems, this charging current, as it is called, may attain considerable magnitudes.

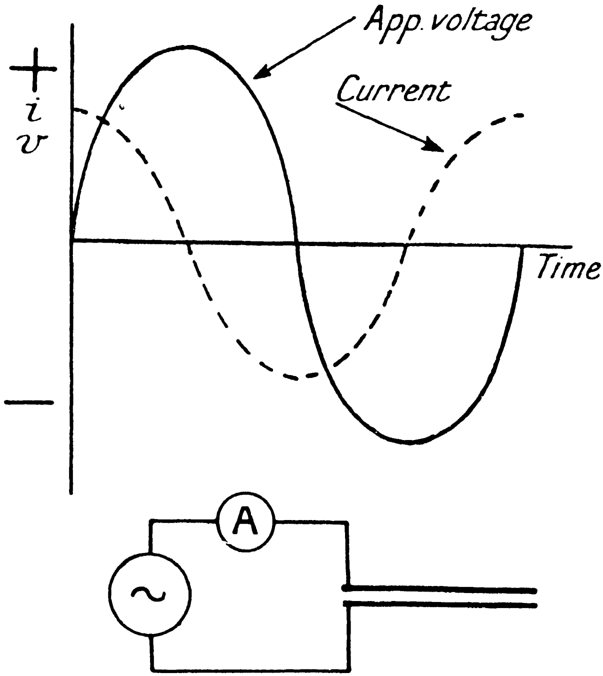


FIG. 164.

It is not possible in this book to prove the formula con necting current and voltage in capacitative circuits when R.M.S. values are employed; it is, however, quite simple and may be written

$$I = \frac{V}{\frac{1}{\omega C}} = V\omega C.$$

$\frac{1}{\omega C}$ is referred to as the capacitance reactance of the circuit

and is expressed in ohms. The fact that the current in a capacitance leads the voltage by a quarter of a cycle is extremely important and use may be made of artificial condensers, for the production of leading currents in parts of circuits, in order to neutralise lagging currents in other parts of the same circuit.

Example.—A two-core cable 10 miles in length is used to connect a generating station with a sub-station. If the capacitance between the cores of the cable is 0·3 microfarad per mile and the voltage supplied by the generating station is 6600 at 50 cycles per second, calculate the charging current taken by the cable.

$$\text{Now } I = \frac{V}{\frac{1}{\omega C}} = \omega VC = 6600 \times 6{\cdot}28 \times 50 \times 0{\cdot}0000003 \times 10$$

$$= 6{\cdot}22 \text{ amperes.}$$

The currents and voltages in this example are, of course, R.M.S. values. If the frequency of the supply is doubled, the current, other factors remaining constant, will also be doubled.

POWER IN ALTERNATING CURRENT CIRCUITS

It is obvious that, at any instant, the value of the power may be found by multiplying together the instantaneous values of current and voltage and, since these quantities are constantly changing, we shall expect to find large fluctuations in the instantaneous value of the power at different parts of the cycle. In Figure 165a the current and voltage waves are plotted for a circuit composed of a non-inductive resistance; they are, of course, in phase. The power is calculated at each instant by the method indicated above and is shown by the dotted line. The question arises as to how we shall express the magnitude of this power wave and we do so by stating the average value during a cycle. Note that when stating effective magnitudes we do not use the same method for power as we decided to use in cases of current and voltage (see page 230). This difference arises from the facts that in the case of current (or voltage) the usefulness from the point of view of heating (or other power purpose) is proportional to the square of the magnitude, while, in the case of power, the usefulness is simply proportional to the magnitude.

We see, therefore, that

$$P = \text{average power} = \text{average value of } i \times v \text{ during one cycle,}$$
$$= \quad ,, \quad ,, \quad i^2 \times R \quad ,, \quad ,, \quad ,,$$
$$= I^2 \times R.$$

So long as we are dealing with non-inductive circuits this may also be written as IV or $\frac{V^2}{R}$.

These are the ordinary expressions used in direct current cases but it should be particularly noted that, while the R.M.S. values of current and voltage are employed, the power is given as the average value during the cycle.

We will now consider cases where current and voltage are not in phase, first taking an extreme case where the phase difference is a quarter of a period as in a purely capacitative or in a purely inductive circuit, the latter case being taken as an example. The conditions are shown in Figure 165b and when calculating the value of the power we must remember that at instants when current and voltage are both positive, or both negative, the product will be positive indicating what we may call positive power, while at instants when current is positive and voltage negative, or vice versa, the product will be negative, thus indicating what we may call negative power or power passing in the opposite direction along the circuit. Taking due care in this matter of the sign, we find that the power curve is as indicated by the dotted line and, if we regard the circuit as one in which an alternator is supplying current to a choking coil, we see that at certain instants, while current is rising in either direction, power is passing from the alternator to the choking coil where energy is stored for the time being. At other instants, when current is falling, power is being returned from the choking coil to the machine which is thus acting for the time being as a motor. The average value of the power over a complete cycle is seen to be zero and we have what is termed a wattless or idle current. In practice, of course, we do not find circuits with absolutely no resistance and the presence of even a small resistance, or any other source of loss, modifies conditions to some extent. The most usual case in practice is, therefore, intermediate in

nature between the two extreme cases considered above and we have current differing in phase from the voltage by some angle between no degrees and ninety degrees.

In Figure 165c we have a current wave lagging some thirty

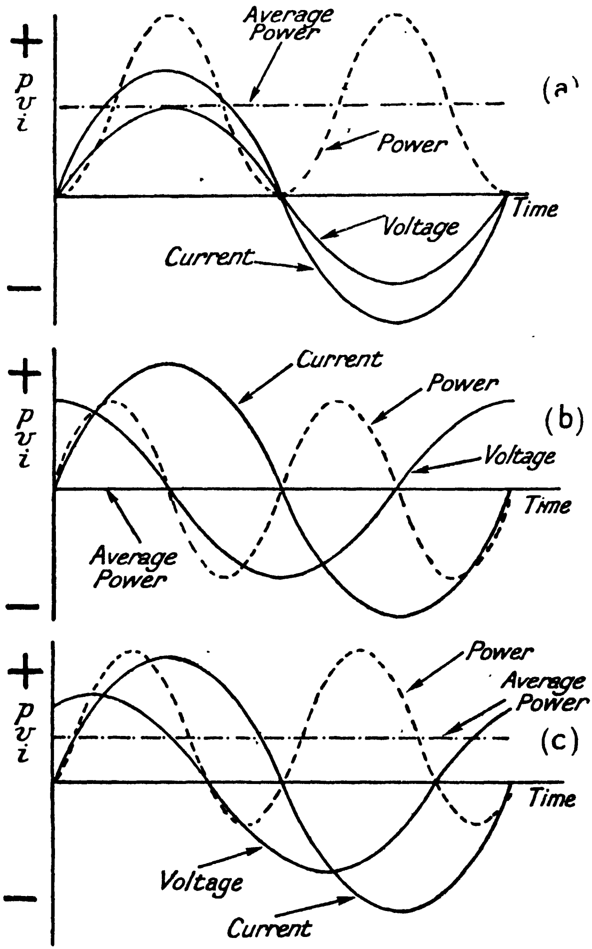


FIG. 165.

degrees on the voltage wave and, calculating the power wave as before, we find it to be as shown by the dotted line, thus indicating a definite average value of the power over the complete cycle though not so large an average value as would have been the case if the voltage and current waves had been in phase. Quantitative ideas concerning the power in circuits of the type under notice are best obtained from an equivalent vector diagram such as is shown in Figure 166, where OV represents the voltage and OI represents the current; the statements made in the following lines concerning this diagram must, however, be largely of a dogmatic nature. On page 236

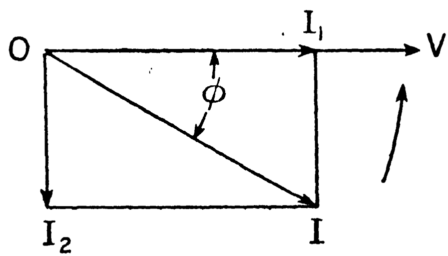


FIG. 166.

we had occasion to find the vector sum of two alternating quantities; we now need to perform the reverse operation and split a current up into two components, one in phase with the voltage and the other at right angles to the voltage and in the Figure the former is shown by OI_1 and the latter by OI_2. Note that the resultant current is the diagonal of the parallelogram whose sides are the two components and thus the conditions are quite similar to the conditions relating to the voltages on page 236. Now the power of the total current is equal to the sum of the powers of its two components and since the power of OI_2 is zero (due to the fact that it is at right angles to the voltage) the total power of the current OI is equal to the power of its component OI_1 which is $V \times OI_1$. A slight knowledge of trigonometry tells us that $\frac{OI_1}{OI}=\cos\phi$ or $OI_1=OI\cos\phi$ and the power due to the current I and the voltage V is $VI\cos\phi$.

We see, therefore, that the power in an alternating current circuit depends not only on the magnitudes of the current and voltage but also on the angle of phase difference between the two quantities. The true power is IV cos ϕ watts and the simple product of I and V is termed the volt-amperes in the circuit. The ratio $\frac{\text{true power}}{\text{volt-amperes}}$ is termed the power factor of the circuit and, so long as the waves are of sinusoidal form, it is equal to $\frac{IV \cos \phi}{IV} = \cos \phi$.

Importance of high power factor in cables and other circuits.—Consider the case of the transmission along a cable of a power of 100 kW at a voltage of 400. If the power factor of the circuit taking the power is unity, the necessary current will be $\frac{100 \times 1000}{400} = 250$ amperes. If now the power factor of the circuit is lower, say 0·8, the current will be

$$\frac{100 \times 1000}{400 \times 0{\cdot}8} = 312{\cdot}5 \text{ amperes.}$$

This larger current will mean added expense in the transmission because, if we keep the area of cross-section of the cable unaltered, we shall have a greater loss taking place (the loss in transmission depends upon I^2R) or, alternatively, if we wish to keep the losses unaltered, we shall need to employ a cable having a lower resistance (i.e. of greater area of cross-section) which will involve us in higher first costs which, in turn, will mean higher annual fixed charges. The same arguments apply to the losses incurred, and the amount of copper required, in machine windings and we see that it is of the highest importance that power factors of alternating current circuits and machines should be as high, that is as near unity, as possible. In considering the question of power factor we have had in mind a case where current was lagging with regard to voltage (this is the most usual case in practice) but the same considerations apply to cases where current is leading the voltage.

Improvement of power factors of loads.—The chief sources of low power factors in systems are induction motors and transformers, particularly when these appliances are lightly

loaded. In such cases the current will be lagging with respect to the voltage and several methods are available for the improvement of the power factor of the total load when this condition exists. One of these methods is a simple application of the use of capacitance and is briefly described below. In the vector diagram shown in Figure 167, OV represents the line voltage and OI represents the lagging current taken by an induction motor. If, in parallel with the motor, we place an artificial capacitance (composed of two sets of conducting plates separated by thin layers of suitable insulating material), an additional current will be taken from the line. This current will lead the voltage by practically 90° and is shown by OC in the diagram. The resultant current taken from the line may be found by the usual method of vector addition and is represented by OD. If OC is of suitable magnitude (this will be determined by the magnitude of the capacitance) the resultant current may be brought into phase with voltage and the power factor of the complete load brought up to unity. It is not absolutely necessary to use a condenser to provide the desired leading current when improving power factor in this way, any other device which can be connected in parallel with the load and which will take a leading current will effect the desired result. It will be noticed in the diagram that the resultant current is less than the current taken by the motor alone; this will result in lowering the cost of transmission of power, either by allowing the use of less copper in the line or

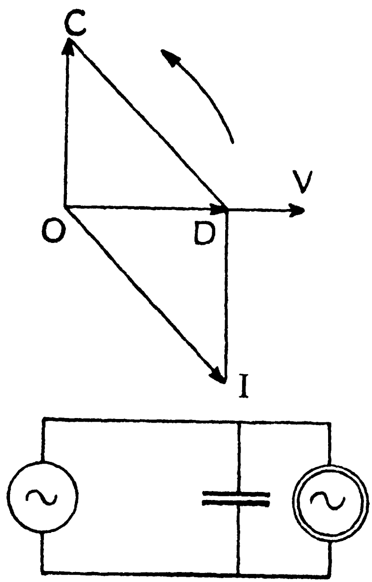


FIG. 167.

by lowering the line loss or perhaps by a combination of both advantages. In many cases the economy effected in these ways will, in a few years, cover the entire cost of the provision of the condenser, the running and maintenance costs of which are very low. Power consumers are often charged on the basis of a fixed annual charge per kVA[1] of maximum demand plus a small charge per unit of energy consumed; in such cases the use of a condenser in the manner described above lowers the maximum kVA demand and in so doing lowers the annual bill of the consumer concerned.

Rating of alternators and transformers.—If we desire to give an indication of the capacity of a direct current machine we usually state the voltage and permissable output in kilowatts. From this information the current output can at once be obtained. When, however, we desire to state the output of an alternator or transformer it is not very satisfactory to simply state the voltage and output in kilowatts because this information does not determine the current rating, since the power factor is not known, and thus gives but a poor idea of the size and cost of the machine. A transformer capable of giving an output of 100 kW at unity power factor will be a much smaller and cheaper appliance than one capable of giving an output of 100 kW at a power factor of say 0·8, since the latter machine must be capable of carrying larger currents and must contain more copper. In such cases it is better to state the rating by giving the voltage and the output in kilovolt-amperes, the current capacity is then definite and can readily be obtained. The rating will be still more definite if we state the lowest power factor on which the machine is intended to operate, but, as a single item of information, the kVA output of a machine is much more useful than the kW output of a machine.

POLYPHASE CIRCUITS

In the chapter dealing with alternating current generators, we saw, in the case of single-phase machines, that it was desirable to concentrate the armature winding to a certain

[1] By kVA is meant the kilovolt-amperes of the circuit which is $\frac{\text{current} \times \text{voltage}}{1000}$ in a single-phase case.

extent in order to avoid loss of E.M.F. due to the generation of opposing voltages in conductors connected in series. This concentration leaves vacant spaces on the armature and it is possible to fill these up by the provision of one or more additional armature windings. From these independent windings we shall get a corresponding number of independent E.M.Fs. which will have equal magnitudes (if the several windings are similar) and equal frequencies, but will have definite and constant phase differences whose magnitudes will be settled by the relative positions of the windings on the armature. The currents obtained from these windings, which may, if desired, be fed to quite independent circuits, are referred to as polyphase currents. If two similar windings are placed on the armature they will each occupy 50 per cent of the total space available and the voltages in the two windings (or phases) will differ in phase by 90°. If currents are sent by the two windings through similar loads, the currents will also differ in phase by 90° and are referred to as two-phase currents. If three similar windings, the most usual number, are placed on the armature, they will each occupy one-third of the total space available and the voltages in the three windings will differ in phase from each other by 120°.[1] Currents sent by these voltages through similar loads will also differ in phase by 120° and are referred to as three-phase currents.

Balanced polyphase circuits.—If the voltages, currents, and phase differences between voltage and current, have equal values in all phases of a polyphase circuit, the system is said to be balanced. If these conditions are not fulfilled the

[1] As a matter of fact, the phase difference between the voltages produced in any two of the windings may be looked on as being either 60° or 120° depending upon which end of a winding we consider as the commencing end. If we reverse our idea as to which end constitutes the commencement of a winding, we reverse the direction of the corresponding voltage vector, and a phase difference which has been 120° is converted into a phase difference of 60°. Thus, in Figure 168, if the vector OA represents the voltage in AB, looking on A as the commencing end, and OD represents the voltage in DC, looking on D as the commencing end, then, if we look on C as the commencing end of the second winding, the voltage in it, relative to the voltage in the first winding, will be represented by the vector OD_1. The usual plan is to look on the three voltages as differing in phase from each other by 120°, thus making a symmetrical arrangement.

system is said to be unbalanced. When the load in a polyphase system consists of polyphase induction motors the system is usually fairly well balanced but if the load is composed of lighting or includes single phase motors, it is likely to be unbalanced.

Interconnection of polyphase systems.—It is possible to keep the leads and loads of the several phases in a polyphase system quite separate and distinct from each other and it is also possible to interconnect the several phases. The choice as to the more desirable course to adopt depends upon the number of phases employed and also upon the circuit conditions.

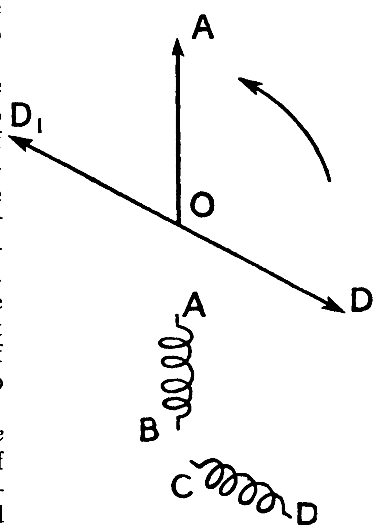


FIG. 168.

Interconnection in two-phase systems.—Only one mode of interconnection is possible—that in which one lead is used as a common conductor of the two phases. This arrangement is shown in Figure 169 where the upper portion represents a very simple 4-pole alternator winding having one conductor per pole per phase. The lower left-hand part of the Figure indicates the circuit connection in a somewhat different way, the two windings being shown at right angles to indicate that the voltages in them have a phase difference of 90°. A vector diagram to illustrate the phase relationships of the various quantities is shown in the lower right-hand part of the Figure and in this OV_{aa_1} represents the voltage in the phase aa_1 and OV_{b_1b} the voltage in the phase b_1b. The voltage between the lines A and B is the resultant of the addition of the two phase voltages. The addition must be vectoral (since the two voltages are not in phase) and the magnitude of the resultant is $\sqrt{2}$ multiplied by the voltage in either phase. In a similar way the current in line O is compounded of the two phase currents and, if the load is balanced, will

be equal to $\sqrt{2}$ multiplied by the current in line A or line B. The advantages of interconnection in the two-phase case are not great and in some circuits (those containing rotary convertors) interconnection is not permissible.

Interconnection in three-phase systems.—[1]Two simple methods are possible and both are used in practice :—

(*a*) The star method.

(*b*) The mesh or delta method.

The star method.—In this method three ends, one of each phase, are joined together to form a common point known as the star point, the remaining ends being connected to the outgoing line conductors. It will not suffice to select the three ends which are to be connected to the star point in a haphazard manner, they must be three corresponding ends of the three windings. In Figure 170 we have a developed view of a simple three-phase winding having one conductor per pole per phase and which is suitable for use with a four-pole field system. The shaded areas represent the positions of the poles relative to the conductors at a particular instant. The phase windings are labelled aa_1, bb_1, and cc_1 and the ends marked a, b, and c are chosen so that the voltages in the three windings, going through the windings in the directions a_1 to a, b_1 to b, and c_1 to c, are at 120° apart as may be seen from an examination of the relative positions of the windings on the armature. In the Figure the ends which are joined to form the star point are a, b, and c, the remaining ends a_1, b_1, and c_1 being connected to the line conductors. An alternative method for starring the windings would be to join a_1, b_1, and c_1 to form the star point and connect a, b, and c to the line conductors.

No combination of ends to form the star point, other than the arrangements mentioned, will give the desired phase relationships.

In the vector diagram shown in the lower part of Figure 170, OV_{a_1a}, OV_{b_1b}, and OV_{c_1c} represent the voltages in the three-phase windings. If the load on the machine is assumed to be balanced and of a partially inductive nature, the currents in the three-phase windings will be represented by OI_{a_1a},

[1] Other, rather more complicated methods, are also occasionally employed.

OI_{b_1b}, and OI_{c_1c}. Since each phase winding feeds directly into a line, these vectors will also represent the currents in the lines A, B, and C. It will be noticed in the circuit diagram in the upper part of the Figure, that the voltage between

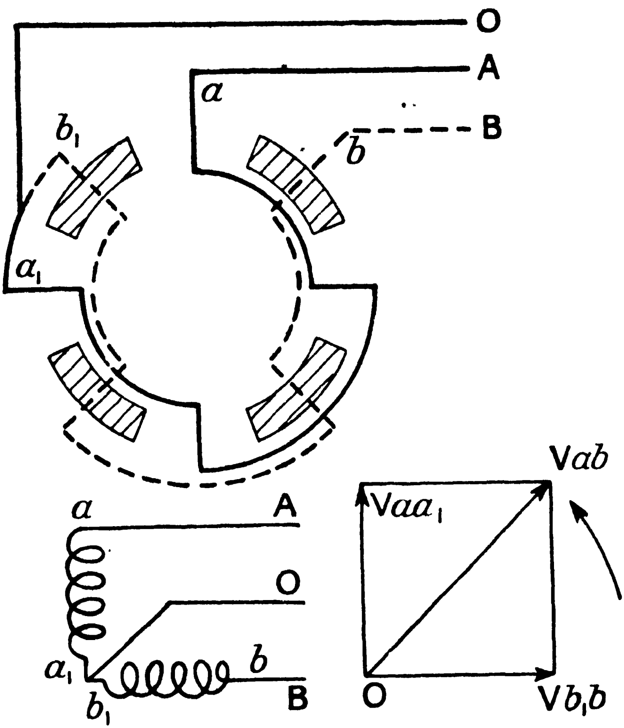


FIG. 169.

two lines is compounded of two phase voltages but it is important to realise that the two phase voltages are not added at 120°. For example, consider the voltage between the lines A and B. This is made up of the voltage in the winding a_1a (going in the direction a_1 to a) added to the voltage in the winding bb_1 (going in the direction b to b_1, ***not*** in the direction b_1 to b). The effect of this apparently small

point is that the voltage in the phase b_1b is reversed relative to its position in the vector diagram and it now takes up the position $-V_{b_1b}$. The net result is that the line voltage between A and B is made up of two phase voltages added at

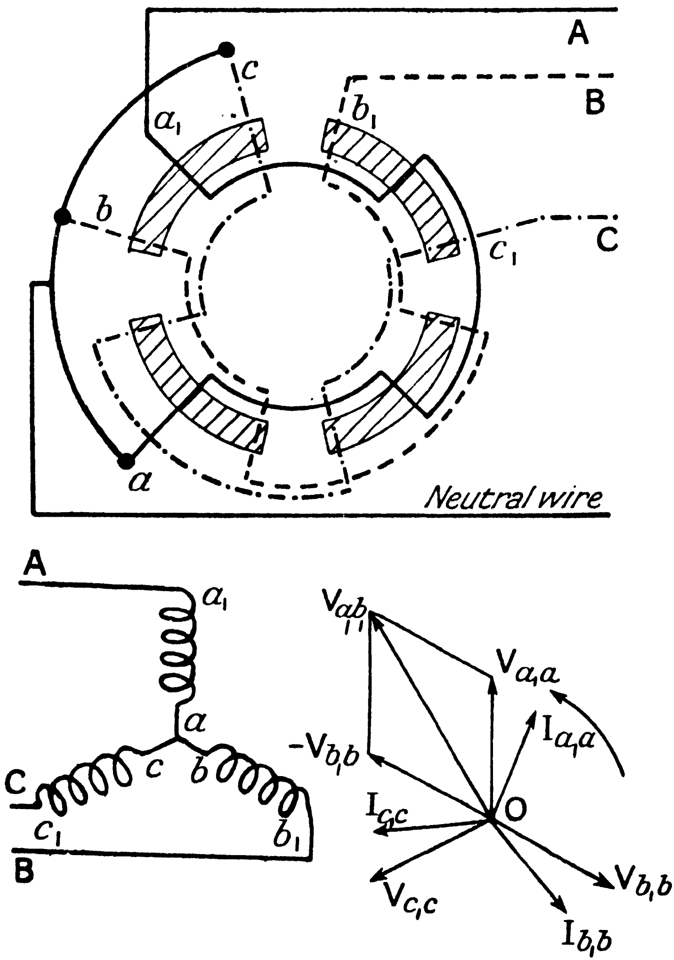


FIG. 170.

an angle of 60° as shown in the Figure by OV_{ab_1}. In a similar manner the voltages between the other pairs of lines may be obtained.

Application of simple trigonometry to the vector diagram will demonstrate that the line voltage $=\sqrt{3}\times$ phase voltage or $1{\cdot}732\times$ phase voltage. In a three-phase star-connected system working on a balanced load, only three line conductors are essential since it can be shown that in these circumstances, with sine waves, no current would flow in a line conductor connected to the star point if it was provided. On the other hand, if the load is unbalanced, a fourth line conductor to the star point is necessary, though its section may be less than that of the other three line conductors. This arrangement, known as a three-phase four-wire system, is largely used for distribution at low and medium voltages, the lighting load being divided into three parts, one part being connected between each line conductor and the conductor connected to the star point. This part of the load is likely to be unbalanced. Three-phase motors may be connected across the three main conductors only, since the load in this case is balanced, thus taking advantage of the higher voltage available. If the lamp voltage is V (say 230), the line voltage for the motors will be $\sqrt{3}\times V$ (or 398·4).

The mesh or delta method.—In this method the windings are connected so as to form a closed internal circuit, the three line conductors being connected to the three points of junction of the phase windings. The ends for connection to each other are selected so that the three voltages are, as regards the closed internal circuit, at 120° from each other with the effect that the resultant voltage round the closed circuit is zero. In Figure 171 we have the same arrangement of conductors on the armature as in Figure 170 and the three junctions are formed by joining a and b_1, b and c_1, and c and a_1. An inspection of the Figure shows that for the case of mesh connection the voltages between lines will be equal to the voltages in the phases. It will also be seen that each line current is compounded of two phase currents and considerations similar to those used in connection with the line voltage in the case of star connection, lead us to add these currents at an angle of 60° with the result, for balanced loads, that the line current is equal to $\sqrt{3}$ or 1·732 times the phase current.

Calculation of power in three-phase circuits.—If we have a balanced star-connected load the voltage (line to star point), current, and phase angle in each phase being V_p, I_p, and ϕ respectively, the total power is clearly $3\ V_pI_p \cos\phi$. Further,

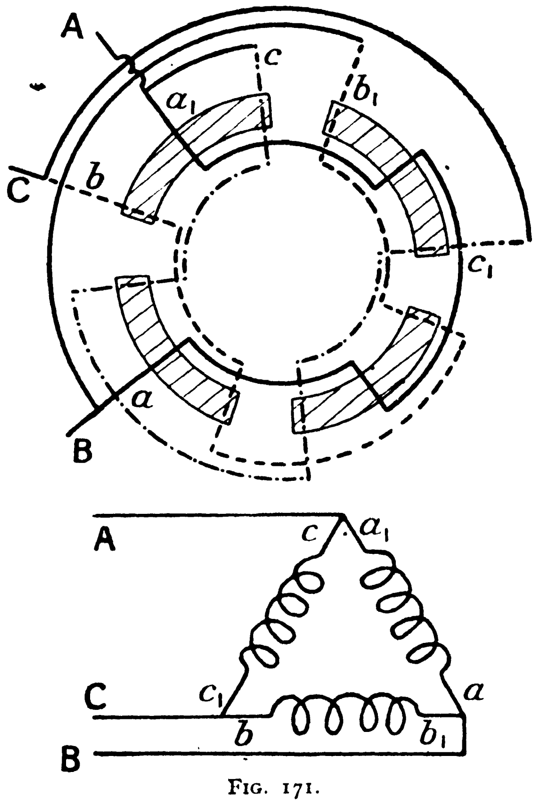


FIG. 171.

if the line voltage and current are denoted by V_l and I_l, we have $I_p = I_l$ and $V_l = \sqrt{3}\ V_p$, and we may also write that the total power is equal to $\sqrt{3}\ V_lI_l \cos\phi$ or $\sqrt{3}\ V_lI_l$ multiplied by the power factor.

A similar investigation shows that the same formula

applies in cases of mesh connection. Care must be taken to apply this formula only to cases where the load is balanced. If it is required to calculate the total power in the case of an unbalanced load, it is perhaps best to calculate the power in each phase separately and then add.

Measurement of power in three-phase circuits.—When the load is balanced it is permissible to connect a wattmeter to indicate the load in one phase (if the star point is accessible), the total power then being obtained by multiplying by 3. A more generally used method is that known as the two wattmeter method in which two wattmeters are connected to the

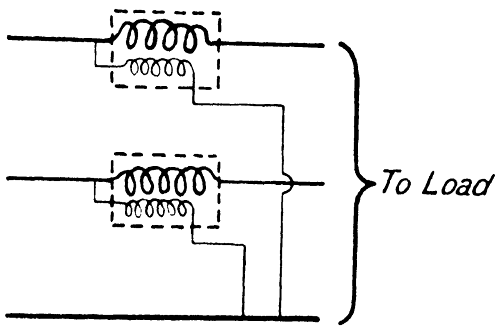


FIG. 172.

circuit as indicated in Figure 172. With this arrangement it is not difficult to show that the algebraic sum of the readings of the two meters gives the total power in the circuit whether the load is or is not balanced. It is necessary to take the algebraic sum because, if the power factor of the circuit is low, one of the meters may tend to read backwards. This scheme of connection is also suitable for energy meters in cases where the total consumption of energy is required.

Advantages of interconnection in three-phase circuits.—In the first place we diminish the number of lines which means greater simplicity in the line itself and also in the switch gear and other appliances. Further, a considerable saving of copper can be made in the line and this point is brought out in the following example.

Suppose that we wish to transmit 100 kW at unity power factor, the R.M.S. voltage between lines not to exceed 500. If we transmit the power by single-phase current, two lines will be needed and the current per line will be

$$\frac{100,000}{500}=200 \text{ amperes.}$$

If we work our conductors at 1000 amperes per square inch, the total area of cross-section will be 0·4 sq. in.

If we transmit the same quantity of power by three-phase circuits without interconnection, one-third of the power will be transmitted per phase and the current per conductor will be $\frac{100\times 1000}{3\times 500}=66{\cdot}7$ amperes. Thus, with the same current density as before, the sectional area of each conductor will be 0·0667 sq. in. and, since there are now six conductors, the total area of cross-section will be 0·4 sq. in. as before.

Now if we have a three-phase interconnected transmission (assuming the load to be balanced) we have $P=\sqrt{3}\,V_l I_l$ or

$$I_l=\frac{P}{\sqrt{3}V_l}=\frac{100,000}{1{\cdot}732\times 500}=115{\cdot}5 \text{ amperes.}$$

Using the same value of current density as before, the sectional area per conductor will be 0·1155 sq. in. and, as there are three conductors, the total sectional area will be 0·3465 sq. in. thus showing a considerable saving in the amount of copper needed.

If we denote the resistance per line in the single-phase case by R_1, the resistance per line in the three-phase case will be $R_1\times\frac{0{\cdot}2}{0{\cdot}1155}$ or $1{\cdot}732\,R_1$. The transmission losses in the single-phase case will be $2\times 200^2\times R_1=80,000R_1$ watts. This figure will also be true for the three-phase case with no interconnection. The transmission losses in the three-phase interconnected case will be $3\times I_3^2\times R_3=3\times I_3^2\times 1{\cdot}732\times R_1$ $=3\times 115{\cdot}5^2\times 1{\cdot}732\times R_1=69,310R_1$.

Thus, if we keep to a constant value for the current density in the conductors, not only will there be a saving in the amount of copper required but also a diminution in the amount of the loss in the lines.

As a further exercise we may consider the amount of copper required if we decide to have equal losses in the single-phase case and in the three-phase interconnected case. We shall then have

$$2 \times 200^2 \times R_1 = 3 \times 115 \cdot 5^2 \times R_3$$

$$\text{or} \quad \frac{R_3}{R_1} = \frac{A_1}{A_3} = \frac{2 \times 200^2}{3 \times 115 \cdot 5^2} = \frac{1}{0 \cdot 5}.$$

Where A_1 and A_3 are the areas of cross-section per line in the single- and three-phase cases respectively.

If A_1 is taken as 0·2 sq. in. (as before) the sectional area per line in the three-phase case will be 0·1 sq. in. and the total sectional area will be 0·3 sq. in. showing an even greater saving than when constant current density was used.

It should be noticed, however, that it is not always possible to take full advantage of the saving indicated in the case where equality of losses is assumed, because it is clear that this will result in increased current density in the three-phase case, and this may not be permissible owing to the increased heating thereby produced in the conductors.

CHAPTER XI

INDUCTION MOTORS

THE induction motor, which has made great headway in recent years, involves the application of two distinct principles. The first, originally enunciated by Arago, embodies the idea that when a conductor is cut by the lines of a moving magnetic field, an induced voltage is produced within it, and, if the arrangement of the conductor is such that the voltage can send a current, the interaction between the main magnetic field and the magnetic field produced by the current will tend to drag the conductor in the wake of the moving field. In Figure 173, the portion A is supposed to consist of an iron core provided with a shaft mounted in bearings, so that the core is free to rotate. Conductors, lightly insulated from the core, are situated in slots or tunnels arranged at regular intervals round the core. At each end of the core a copper ring (also lightly insulated from the iron of the core) is mounted, on to which the ends of the straight copper conductors are connected with good mechanical and electrical joints. Now imagine that the outer field magnet, which is supposed to have the polarities as indicated provided by a winding carrying a

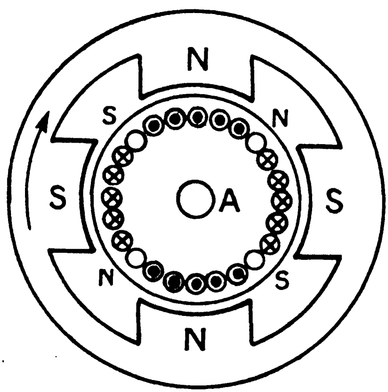


FIG. 173.

direct current, be rotated in the direction of the arrow. There is no need to consider the mechanical arrangements necessary since this particular method of providing a moving field is only used to show the principle of the induction motor. An application of the right-hand rule (remembering to have the palm of the hand facing in the direction of the movement of the conductors relative to the magnetic lines) will show the induced voltages to be in the directions indicated by the symbols in the diagram, and, since the conductors are joined together by the rings at the ends, these symbols will also show the directions of the induced currents. A separate developed skeleton view of the conductors with the directions of the currents indicated in the conductors and in the end rings is shown in Figure 174. The central iron core with the conductors mounted thereon is referred to as the rotor of the induction motor, and the currents in the rotor conductors will give rise to polarities at certain parts of the rotor core as is indicated in Figure 173. A little thought will show that the position and nature of the rotor poles is such that the rotor will tend to move round in the same direction as the main poles. It is important to note that the rotor can never move quite so fast as the main poles, because, if it did, the lines of the main field would not cut the rotor conductors and there would therefore no longer be any rotor voltage or current. There must always be some "slip," as it is termed, of the rotor conductors relative to the main field. The device, as it has so far been described, would be useless from the commercial point of view because the method for providing the moving magnetic field is clumsy and inconvenient.

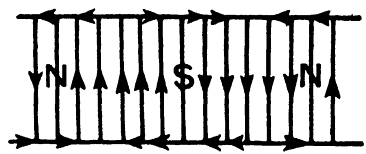


FIG. 174.

About the year 1885 Ferraris described a much more practical method for providing the necessary rotating magnetic field.[1]

His method involved the use of polyphase currents circulating

[1] A rotating magnetic field is one whose magnitude is constant but whose direction progressively changes. The magnetic system in Figure 173, when revolved, produces a rotating field.

in suitable windings on a laminated iron core, there being no mechanical motion of the windings or of the core. The principle of the method can be followed by considering the

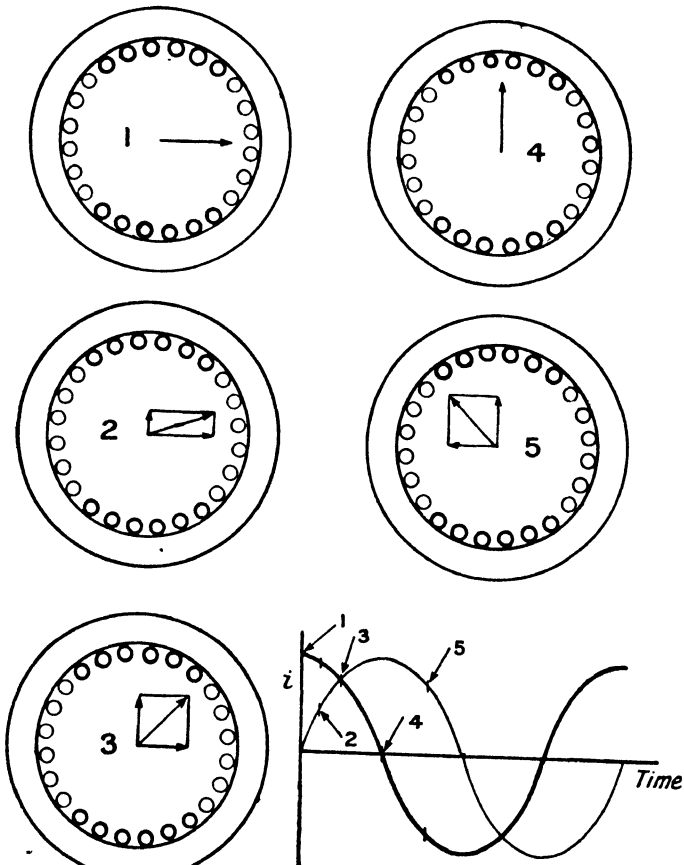


FIG. 175.

two-pole, two-phase, case indicated in Figure 175. Here we have a laminated iron ring on the inner surface of which two sets of conductors are shown, the thick circles indicating the

conductors of the first phase and the thin circles indicating the conductors of the second phase. The conductors of each phase will be suitably connected together to form a winding but the type of the end connections is quite immaterial; in practice they will probably be arranged in the drum fashion. When the conductors shown by the thick lines are traversed by the current obtained from one phase of the two-phase supply, a horizontal magnetic field will be produced which will vary in magnitude as the current varies. Also, when the conductors indicated by the thin lines are traversed by current obtained from the second phase of the two-phase supply, a vertical magnetic field will be produced which also will vary in magnitude as the current varies. We shall therefore have in the centre of the core two component fields which are at right angles as regards direction and are also at right angles as regards phase (since they are produced by the two currents of a two-phase system which differ in phase by 90°). These two component fields may be described as alternating (as distinct from rotating) fields, an alternating field being one whose line of action is unvarying but whose magnitude and direction along that line of action vary. Now the resultant of two alternating fields, disposed in the manner indicated, is a rotating field, and it should be noted that this rotating field is produced without motion of either core or conductors. The mode of production of this rotating field is shown in the figure where the state of affairs at the several successive instants of time indicated in the wave diagram is shown in a series of diagrams. In each diagram the magnitudes of the two component fields are shown for the appropriate instant and the resultant field is also drawn; this, it will be seen, remains constant in magnitude but progressively changes in direction. The rotating field thus produced is identical in character with that produced by the field system shown in Figure 173, but is obtained in a much more convenient manner, and, if this method for producing the rotating field is used with the type of rotor previously described, we have the principle of the modern polyphase induction motor fully exemplified. In the simple explanation given above we have not considered the effect of the current in the rotor on the magnetic field in the gap. It is not possible to consider the point in detail at the moment, and it will suffice to say that

increasing load on the motor causes increased rotor current (the slip will also increase) and the magnetic effect of the rotor current on the gap is balanced by increased current in the stator (the additional current being termed the stator load current), the whole effect being very similar to that produced in the static transformer when secondary current is allowed to flow. The resultant strength of field in the gap is, for a certain motor, dependent only on the applied voltage and is essentially constant at all loads. Though, for the sake of simplicity, we have considered the use of two-phase currents in the above explanation, three-phase currents may be employed in a similar way (if an appropriate winding is used), and, as a matter of fact, are much more commonly used in practice. Any type of armature winding used in connection with alternators can be employed for the stators of induction motors and, if supplied with suitable current, will produce a rotating magnetic field. The stator core must be built up of fine laminations, but there is not the same vital need for finely laminating the rotor core since the frequency of the reversals of magnetism in the rotor core is, when the machine is running at full speed, quite low. As a matter of fact, if a solid mass of iron is used for the rotor core the machine will operate quite well. One great advantage of the induction motor is that no sliding contacts are essential; it is true that sometimes a proper winding terminating in slip rings is placed on the rotor, but this is done to improve the starting qualities of the motor and does not improve the full speed running qualities.

CONSTRUCTIONAL DETAILS OF INDUCTION MOTORS

Figures 176, 177, 178, and 179 showing views of parts of modern induction motors have been supplied by the English Electric Co., Ltd., to whom the writer is also indebted for the information concerning these machines which is given below. The squirrel cage rotor shown in Figure 176 has a core built up of steel stampings and is provided with axial ventilating ducts of large size. The slots in the core are of the semi-enclosed type and are slightly skewed in order to give uniformity of torque and good starting characteristics. The winding consists of stout copper bars placed in the slots, the current paths being completed by brass end rings which are cast on to the

PLATE I

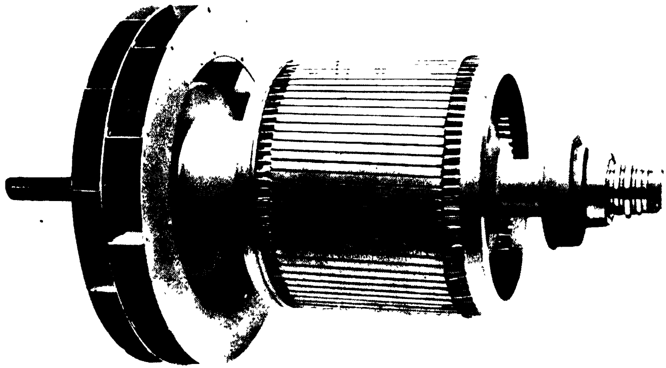


FIG. 176

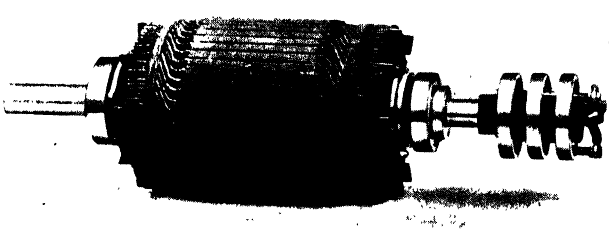


FIG. 177

To face page 262

bars. Adequate ventilation is secured by means of a large fan which sucks cool air through the openings provided in the stator and rotor and drives the heated air radially outwards at the pulley end of the machine. From the Figure it will be noticed that the fan is divided into two parts, the smaller part, more remote from the core, sucking air through the rotor (the necessary path being completed by the space between the shaft and the hollow sleeve shown between the rotor proper and the fan and on to which the fan is fixed), while the larger part of the fan, situated nearer to the core, sucks air through the gap and stator windings.

Figure 177 shows a wound rotor provided with slip rings. Three phases will commonly be provided, one end of each being connected to a star point. The free ends of the windings, which may be formed from either wire or strip material, are taken into the hollow shaft and thus passed through the bearing at the end of the machine remote from the pulley. Outside of the bearing the connections are brought out of the shaft and connected to the slip rings. Figure 178 shows the rings and brushes with the cover removed, and it will be noted that suitable gear, operated by a hand wheel, is provided for shorting the rings and lifting the brushes from the rings after the motor has attained full speed. This arrangement minimises wear on the rings and brushes and cuts down the running losses thus diminishing the slip.

A completely wound stator is shown in Figure 179. The supporting frame is of steel and this carries a laminated steel core having nearly closed slots in its inner cylindrical surface. The winding shown in the Figure, which is suitable for the smaller sizes of machines, is of the mush type and is formed by winding the coils to shape and then inserting them into the slots by passing the wires separately through the comparatively narrow slot openings, the end portions of the coils being subsequently taped up and impregnated. Larger machines are provided with a concentric type of bar winding, the conductors being formed to shape, insulated and impregnated, and then pushed through the slots, the connections between the several conductors being completed by electric welding.

The bearings are of the ball or roller type, depending on the size and duty of the machine, the advantages gained by the

adoption of such bearings, as against bearings of the bush type, being, ease of starting, absence of wear resulting in permanency of uniformity of the air gap, and elimination of oil which may cause harm to the windings.

The absence of oil also gives freedom in arranging the motor in any position required by the machine which it is arranged to drive.

FACTORS INFLUENCING THE PRODUCTION OF TORQUE IN AN INDUCTION MOTOR

The torque, or turning moment of any motor, is the product of the total force exerted on the moving conductors and their radial distance from the centre of the shaft. It is clear that the force driving the conductors will be dependent on the current in the conductors and on the strength of the field in which they are immersed. We shall therefore only get the maximum effect for any value of rotor current when the conductors carrying large values of current are situated in the regions of strongest field, and this may or may not be the case, depending on the conditions of operation. Figure 180*a* is a diagram representing a two-pole motor, the position of the rotating field at a certain instant being shown by the radial lines in the gap. It must be understood that this field is revolving in the gap at a speed dependent on the frequency of supply and on the number of poles for which the motor is wound. At the instant shown in the Figure, certain of the rotor conductors are situated in the strongest field and in these conductors there will occur, at that moment, the highest values of E.M.F. caused by the relative motion of the field and the rotor conductors. Under all conditions the conductors having the highest values of E.M.F. in them at any instant will be those lying in the strongest parts of the field. If the rotor current is in phase with the voltage we shall therefore have the conductors through which high current is passing immersed in the strong parts of the field which, as we have seen, is the condition favourable for the production of high torque. Figure 180*b* represents rather a different condition of affairs. In this case the rotor current is supposed to be lagging with reference to the rotor voltage, and this results (owing to the revolution of the field round the gap) in the conductors carrying large current being immersed in parts

PLATE

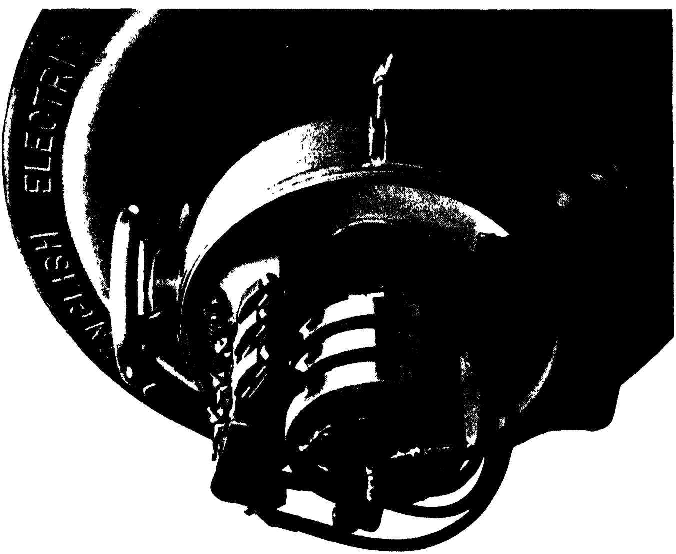


FIG. 178

FIG. 179

of the field where the strength is less than the maximum, giving, for the same value of rotor current, less torque than was produced in the previous case.

As a matter of fact we may say that

$$\text{Torque} \propto \text{Rotor current} \times \text{Field strength} \times \cos \phi_2,$$

where ϕ_2 is the phase angle between rotor voltage and rotor current. Now the rotor conductors have both resistance and inductance, but, when the motor is running at full speed, the slip is small, the rotor frequency is therefore very small (of the order of one cycle per second) and this results in a low value of rotor reactance. There is thus only a small angle of phase difference between rotor voltage and rotor current and the conditions are favourable to good torque production.

At the moment of starting, however, the conditions are very different. The rotor conductors are at rest while the field revolves at full speed immediately the stator switch is closed, with the result that there is a large value of rotor voltage which sends a large value of rotor current, both of these quantities having a frequency equal to that supplied to the stator. With this high frequency, the rotor reactance is much higher

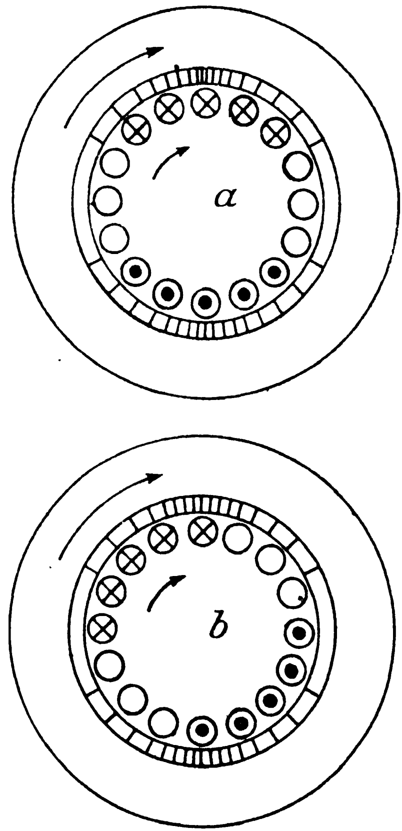


FIG. 180.

than the value corresponding to running at full speed, consequently the rotor current lags very considerably behind rotor voltage and the torque is much less than might at first thought be anticipated from the large value of rotor current concerned. It is to overcome the difficulty of securing a good torque at starting that rotors with windings having their ends brought out to slip rings are sometimes used. With such an arrangement it is possible to insert added resistance in the rotor circuit during the starting period and this, while limiting the magnitude of the rotor (and stator) current, brings it more nearly into phase with the rotor voltage and thus improves the torque. It is possible to obtain considerable torque at starting with squirrel cage rotors, but only by allowing a very large rotor current to flow; this, in turn, causes a large stator current which is objectionable on account of line disturbance.

SPEED OF INDUCTION MOTORS

The speed of the rotating field depends on the number of poles and on the frequency of the supply. During one cycle, two poles of the field must pass a certain point in the gap and we have

$$\frac{\text{Speed of field in R.P.M}}{60} \times \frac{p}{2} = \text{frequency of supply, or}$$

$$\text{Speed of field} = \frac{120 \times \text{frequency of supply}}{p} \text{ R.P.M.}$$

The rotor always slips a little with respect to the field and Speed of motor

$$= \left\{ \frac{120 \times \text{frequency of supply}}{p} - \text{slip in R.P.M.} \right\} \text{R.P.M.}$$

The slip is only a small percentage of the speed of the field, say 1 per cent at no load and 6 per cent at full load. The reason for the fall in speed (due to the greater slip) at higher loads may be seen from the following considerations. If an induction motor is running on no load, the rotor current will take up such a value as will give a driving torque sufficient to overcome the retarding torque due to windage, friction, and other causes, and the slip will be adjusted automatically to such an

amount as will give a value of rotor voltage which will produce this current. When load, or additional load, is put on to the motor, the old value of driving torque will no longer suffice and the motor will slow down to some extent. As it slows down, the slip increases, and this will cause increased values of rotor voltage and rotor current. The rotor frequency, though somewhat higher than at first, is still quite low and is insufficient to cause the rotor current to lag behind the rotor voltage to a material extent. The net result, therefore, is the production of increased driving torque, and a new stable state of affairs is quickly reached when the driving torque is sufficient to meet the new load conditions, the speed of rotation being somewhat lower than at the smaller load.

STARTING OF INDUCTION MOTORS

When starting a motor the vital point is to produce adequate torque to meet the load conditions without causing too much line disturbance due to the use of excessive starting current.

Small squirrel cage motors may be started by switching the stator straight on to the line. It will be realised, from the statements already made, that the starting conditions when this is done will not be ideal, but, owing to the comparatively large starting current taken (several times the full-load current), adequate starting torque will be produced for many purposes. The limit of size of motor to which this method of starting may be applied is usually settled by the authority concerned with the supply of power and is commonly only a few H.P. It is a method much used for the starting of motors employed for the individual driving of looms. In many cases the switch used is of the simple non-automatic type, but it is also possible to procure circuit breakers provided with overload tripping arrangements for the purpose. A diagram of connections for such a breaker is shown in Figure 181.[1]

In this arrangement the switch contacts, having been closed by the external handle, are held in the closed position, against the opening tendency of a spring, by means of a

[1] The writer is indebted to Messrs. G. Ellison, Ltd., for the diagrams shown in Figures 181, 182, and 183, and also for information concerning the appliances.

" no volts " coil. It should be noted that when the switch is closed the moving contacts bridge across from the top set of terminals, which are connected to the lines, to the corresponding terminals in the lower set which are connected to the overload coils, the paths continuing through the over-load coils and then through the three centre terminals to the motor. Over-load coils are placed in all three lines and these will cause the breaker to open in the event of excess current by

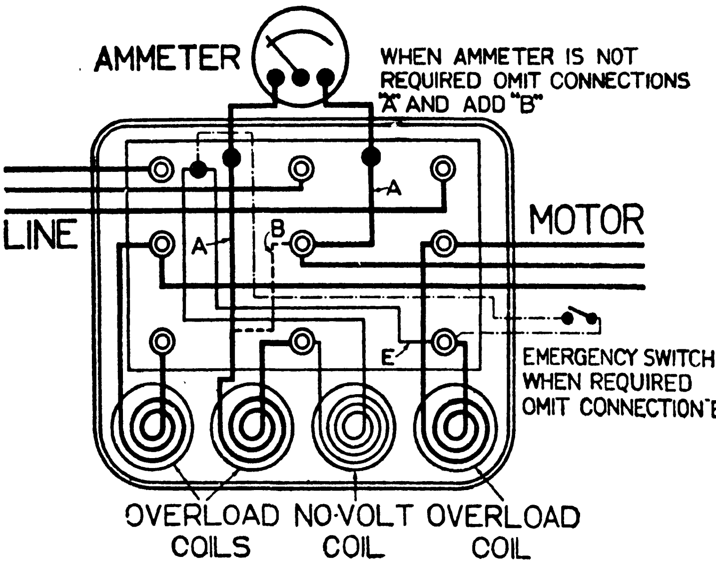


FIG. 181.

opening a contact in the circuit of the no-volts coil. If it is desired to stop the motor from a point remote from the stator, the circuit of the no-volts coil may be run to the point in question and a switch, which is normally closed, inserted; if the knob of this switch is pressed, the switch opens and interrupts the circuit of the no-volts coil and the main breaker at once opens.

Large squirrel cage motors may be started by applying a reduced voltage during the period of acceleration, and it is

important to realise that this method, while reducing the total starting torque available, also reduces the line disturbance, and this is the chief reason for its use. For example, let us imagine in a certain case the starting voltage per phase is 50 per cent of the normal running voltage. Now we have already stated that in the induction motor, as in the static transformer, the gap flux takes up such a value that the induced E.M.F. in the stator windings caused by the rotating flux is but little less than the applied voltage and therefore, with the reduced starting voltage, the necessary induced voltage will be produced with a rotating field having one half of the normal strength. Further, at the moment of starting, the rotor conductors are at rest and the weakened rotating field will only give a rotor voltage and a rotor current having one half of the values of voltage and current corresponding to the direct application of the full voltage to the stator during the period of starting. The phase relationship between rotor voltage and rotor current will be the same whatever the magnitude of the starting voltage, because this depends only on the frequency of the rotor current and this is, at the moment of starting, independent of the magnitude of the applied voltage. Since strength of field and magnitude of rotor current are each halved, the starting torque will be reduced to one quarter of that corresponding to the direct application of the full voltage. In general, we shall find that the starting torque is proportional to the square of the voltage applied to the stator.

USE OF STAR-DELTA STARTING SWITCH

One method of reducing the voltage applied to a three-phase induction motor during starting is to have the six ends of the three windings brought out to the starting switch, which is arranged so that, when the motor is running freely, the windings are connected in mesh thereby causing the voltage applied to each phase winding to be equal to the line voltage. During starting, however, the switch causes the windings to be connected in star and the voltage applied to each phase winding is then equal to the line voltage divided by $\sqrt{3}$. Under this arrangement the strength of field and the magnitude of the rotor current at starting will each be equal

to $\frac{1}{\sqrt{3}}$ of the values corresponding to the application of the full voltage and the starting torque will be $\frac{1}{3}$ of the starting torque produced by full voltage.

The stator current in a phase winding will be equal to $\frac{1}{\sqrt{3}}$ and the stator line current will be equal to $\frac{1}{3}$ of the values corresponding to the direct application of the line voltage to

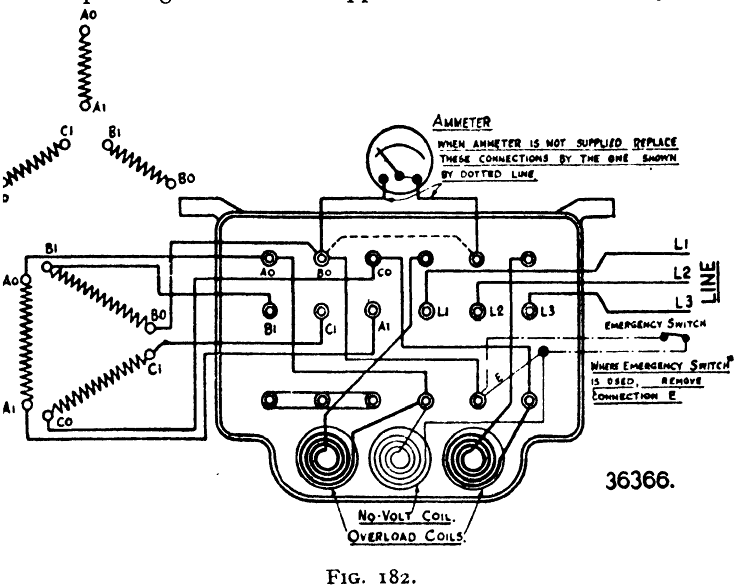


FIG. 182.

the motor with windings arranged in mesh (for a mesh connection the line current is equal to $\sqrt{3}$ times the phase current, while for star connection the line and phase currents are equal, see page 253). The effect of using the star-mesh starting arrangement is, therefore, to reduce the total starting torque and also the line disturbance while leaving the starting torque per ampere of line current unchanged.

Figure 182 shows the connections of a star-delta startor provided with a no-volts coil and with two over-load coils (this number of over-load coils will give adequate protection

against over-loads in many cases). It will be noted that three rows of fixed contacts are indicated in the Figure by double circles. When the moving contacts are in such a position that the centre contacts are connected to the opposite contacts in the lowest row, a study of the diagram will show that the ends B_1, C_1, and A_1 of the motor windings are connected to form a star point while the ends B_0, C_0, and A_0 are connected to the lines L_2, L_3, and L_1, the over-load coils not being in circuit. Further examination will show that when the centre fixed contacts are connected to the corresponding contacts in the top row L_1 is connected to A_0 and B_1, L_2 to B_0 and C_1, while L_3 is connected to C_0 and A_1, the windings are thus arranged in mesh and the over-load coils included in the circuit. The handle of a startor of this type is usually provided with a "sequence" device which ensures that the starting position (giving star connection) is always passed through prior to entering the running position (giving mesh connection).

USE OF AUTO-TRANSFORMER STARTORS

Another method of reducing the voltage applied to the stator during the starting period is to employ a step-down transformer (usually of the auto type in order to economise in copper). Such a transformer is usually provided with several tappings on the low tension side in order that, in any particular case, the lowest tapping which will give satisfactory starting may be employed. It is unnecessary to go into details, but if an investigation be conducted on the lines of that already carried out in the case of the star-delta method of starting, it will be found that this method also gives the same value of starting torque per ampere of line current as would result from directly switching the stator on to the mains. The total starting torque and the total current taken from the line will, however, be reduced to an extent depending on the particular tap in use. Figure 183 shows the connections of an auto-transformer startor. For starting, the moving contacts bridge across the centre and top sets of fixed contacts thus putting the line on to the transformer and the motor on to the selected taps, the over-load coils being cut out of the circuit. In the running position the moving contacts bridge across the centre and bottom sets of fixed contacts, thus

cutting off the transformer and connecting the line directly to the machine, the over-load coils now being included in the

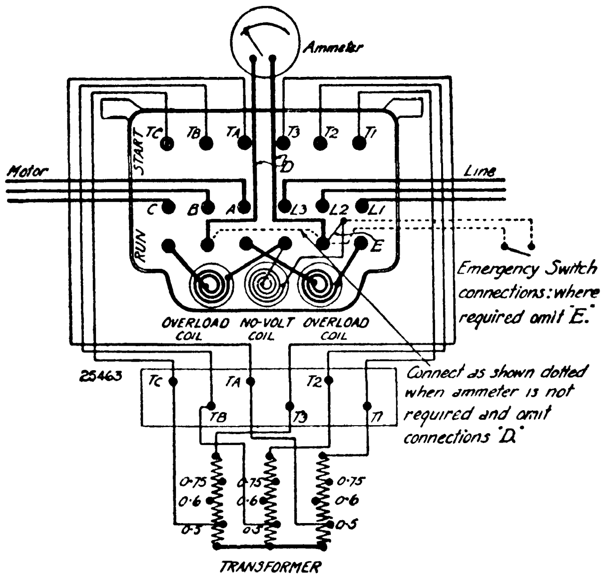


FIG. 183.

circuit. A "sequence" device applied to the handle will also be necessary for this type of startor.

STARTING OF INDUCTION MOTORS HAVING WOUND ROTORS

When the conditions of operation are such that large starting torques are required from induction motors, it is well to use motors with three-phase windings on the rotors, the phase windings being starred at one end and connected to slip rings at the other. During starting the full line voltage may be directly applied to the stator while the rotor windings are connected, by brushes pressing on the slip rings, to a suitable three-legged starting resistance which can be gradually cut out as the motor speeds up. The effect of the added resistance in the rotor circuit is twofold; in the first place it

limits the magnitude of the rotor (and stator) current, and, in the second place, it brings the rotor current and rotor voltage into phase with each other. Thus, since we also have full field strength at starting, the conditions are very favourable for the production of starting torque. With this method it is possible to secure a starting torque equal in magnitude to the full-load torque without exceeding, to any appreciable extent, the current taken by the motor at full load. This is a much better result than can be obtained with squirrel cage

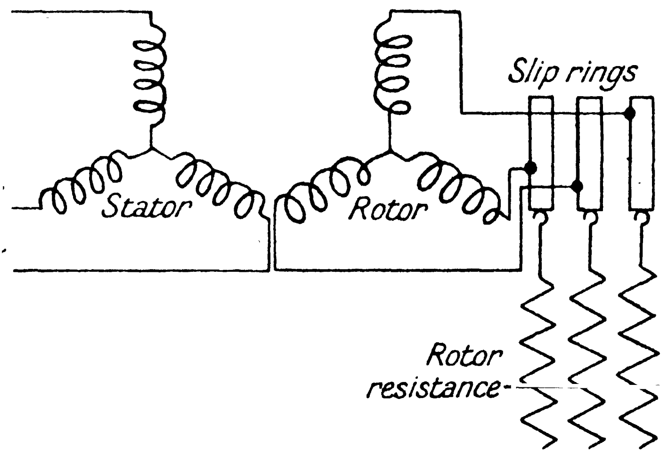


FIG. 184.

motors, and is practically equal to the starting performance of a D.C. shunt motor.

The brushes, brush contacts, and leads introduce a certain amount of resistance into the rotor circuit even when all the steps of the rotor resistance have been cut out, and this state of affairs is undesirable on load (it lowers the efficiency and increases the slip), so that slip-ring rotors are often provided with an arrangement for internally shorting the rings and lifting the brushes after the motor has been started up.

A simple circuit arrangement of a rotor resistance startor is shown in Figure 184, and in practice the gear will usually be

provided with safety devices such as a no-volts coil and with over-load coils in at least two lines. Provision will also be made (by interlocks) to allow the closing of the main switch or circuit breaker to take place only when the handle of the rotor resistance is in the position corresponding to full resistance in the rotor circuit.

REVERSAL OF DIRECTION OF ROTATION OF INDUCTION MOTORS

In Figure 185, if the order of phase rotation in the lines be assumed to be *a*, *b*, *c*, it will be clear that if we change over the connections of two of the lines relative to the motor terminals, we shall reverse the order of phase rotation in the

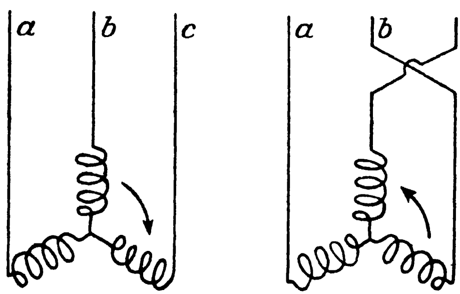


FIG. 185.

motor windings. This will result in a reversal of the direction of rotation of the rotating field and also, of course, in the direction of rotation of the rotor.

SPEED VARIATION OF INDUCTION MOTORS

With the simple induction motor it is only possible to vary the speed by changing the synchronous speed or by changing the slip. The synchronous speed may be varied by a change in the frequency of the supply (which is rarely possible) or by altering the number of poles for which the machine is wound. The number of poles of the machine may be changed by the use of two independent windings on the machine or, in certain cases, by the use of tappings on the winding. If a squirrel

cage machine is in question it is only necessary to make changes in connection with the stator winding (since the number of poles of the rotor winding will be automatically changed by the change in the number of poles in the stator winding), but with wound rotors, it will also be necessary to make corresponding changes in the rotor winding. In any case the method does not produce flexibility of speed change.

Rotor slip (for a certain value of load torque) may be changed by the use of resistance in the rotor circuit in the case of machines having wound rotors, or by altering the voltage applied to the stator in the case of machines having either squirrel cage or wound rotors. As an example of the mode of action of this method, consider the case of a machine having a squirrel cage rotor when the voltage applied to the stator is lowered. Obviously the first effect will be a falling off in speed because the lowering of the stator voltage will result in a diminution of the field strength, and this, in turn, will momentarily cause a diminution of rotor current and the torque produced will no longer be sufficient to meet the requirements of the load. As the speed drops the rotor voltage will increase again, and this will also result in a rise of rotor (and stator) current, and a new stable state of affairs will quickly be reached (with currents in the rotor and stator of considerably higher values than under the original conditions) when the increase of the rotor current will balance, so far as the production of torque is concerned, the diminution of the strength of field in the gap. It should also be noted that the torque conditions in the rotor circuit will not be so favourable at the lower speed owing to the higher frequency of the rotor current, and the increase in the rotor current will also need to be sufficient to make due allowance for this effect. Such methods of speed variation are flexible but very uneconomical owing to the proportionally heavy I^2R losses in the various circuits. In its simple form the induction motor should be regarded as suitable essentially for constant speed work rather than for variable speed work.

CHAPTER XII

LIGHTING CIRCUITS

SUPPOSE we examine a typical modern house service system in order to note the points of chief importance and interest.

To begin with, we find a pair of "service mains" of suitable cross section coming into the building from the much larger "distributing mains" DD running along the street and passing at once to the "main fuses" FF (Figure 186). These fuses, one on each main, are boxed in and sealed up by the supply company, and are not allowed to be tampered with by the consumer.

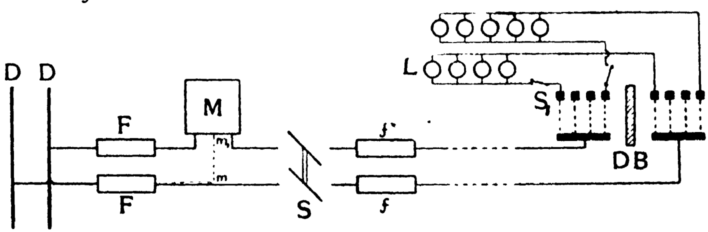


FIG. 186.

Close to these fuses will be placed the meter which serves to measure the energy supplied. This again is fixed and sealed by the supply company, and here their sphere of activity ends and that of the wiring contractor begins. Before the former arrive on the scene at all, the latter has "wired" the building, arranging, in a suitable place readily accessible from underneath the street and close to the positions designed for main fuse and meter, a "main switch" S and another pair of fuses *ff* of smaller capacity, and from thence he runs his cable where required, until it probably ends in a "distribution

board" DB in some convenient and central position, from which branch circuits are led off through yet more fuses either to lamps or to other and smaller distribution boards.

The supply company's fuses are put in merely for their own protection, and are made of such liberal capacity as not to "blow" unless there is something seriously wrong with the house circuit. For this reason it is necessary to have in addition the fuses *ff*, which can be arranged to blow at a moderate overload, such as might be due to the use of lamps of much greater output than the circuit was designed for, or to a slight "fault" somewhere.

When this happens the average consumer will simply put in thicker fuses and go on again as long as he can. Should however, the main fuses blow, an inspector must be called in to replace them, and he will first find out what is the matter.

The exact form of the meter connections will depend upon the type used. It is not a matter of much importance to us at present (see p. 392), but it may be remarked that some merely take the "ampere-hours" into account (voltage of supply being assumed constant). These are frequently termed "coulomb" meters, and are connected up exactly like an ammeter as shown by thick lines in the diagram. Others, known as "energy," or "watt-hour" meters, also take the voltage into account, and to this end contain in addition a winding of high resistance, to be connected directly across the mains, and which carries current at all times, whether lamps are in use or not, although the energy thus consumed of course does not affect the reading, and is not charged to the consumer. Such meters need connections to both mains, and the extra connection may be made by a wire as shown in Figure 186, or the main may be "looped" in (see p. 299); each of these methods necessitate three terminals being employed. Sometimes the additional connection is made by bringing the second main in at one terminal and out at another, the two being simply bridged across; this of course means that the meter has four terminals. In addition to the meter the installation will sometimes be supplied with what is termed a "maximum demand indicator," whose function is to indicate the maximum power taken by the consumer at any one time.

The lamps themselves, as subsequently explained in more detail (see p. 296), are not connected to the larger cables conveying the supply to the various distribution boards, but are arranged in quite small independent groups on circuits fed through suitable fuses from these centres, and in which the current is limited to from 3 to 5 amperes, depending upon the voltage of the supply. For these sub-circuits switches, ceiling roses, lampholders, etc., will be required. In our general survey we have therefore to consider :—

1. Fuses and their holders.
2. The cables and schemes of wiring.
3. The switches.
4. The meters.

Consideration of fittings, such as ceiling roses and lampholders, has been omitted from the present edition, while meters are dealt with in Chapter XIV.

FUSES AND THEIR HOLDERS

Fuses are intended to break the circuit when the current reaches a predetermined value which is in excess of all legitimate requirements and is therefore due to something being wrong.

Although their main purpose is to prevent overheating in the circuits which they protect, it is obvious that a fuse must itself be a source of fire risk, and in designing a fuse holder or a fuse board we must endeavour to make this risk a minimum.

A " fuse " or " fusible cut-out " usually takes the form of a metallic wire fastened between two terminals, but the way in which the wire is taken from terminal to terminal varies very considerably.

The metals most commonly used are tin, lead, zinc, alloys of tin and lead, and copper.

Here much depends on the magnitude of the normal current. For a fuse of given carrying capacity there is much less metal in it if made of copper than if made of a substance having lower conductivity and melting point, and hence if blown violently there is a much smaller bulk of hot metal to be scattered. Against this we must put the fact that for a fuse required to blow under about 10 amperes (for which a

No. 33 tinned copper wire is suitable) copper wires become very small in diameter and are very liable to get in the threads of screws, etc., and in fact are not readily manageable, and then tin is much more suitable.

For larger currents copper is good for the reason mentioned above, and also because of its mechanical strength. It has one disadvantage due to its high melting point. It gets red-hot when carrying about 75 per cent of its ultimate fusing current, so that if raised above this point a large amount of heat has to be radiated or conducted away, much of which goes to heat the fuse holder, making it and its surroundings very hot; and further, when near its fusing point, copper oxidises and gradually deteriorates.

For fuses of large capacity, zinc in the form of strip is now being largely used.

One of the most troublesome points in the design of large fuses is the difficulty in keeping their surroundings cool. In such cases the metal is preferably in the form of strip, to facilitate radiation, though for smaller fittings, such as may usually be met with in distribution boards, wire is more convenient, and tin wire especially so, because it fuses at the very low temperature of 230° C.

Let us now consider what factors will influence the fusing current of a wire of given material. In the first place it is obvious that it will depend upon the diameter of the conductor. If a certain wire fuses at 5 amperes, then two such wires in parallel will fuse at 10 amperes (if they are supposed to exert no influence upon each other). Again, if these two wires are supposed to be merged together to form a single wire having twice the sectional area of either of the constituents, we might expect that it also would fuse at 10 amperes, and that in general the fusing current would be directly proportional to the sectional area of the conductor, i.e. to the square of the diameter. A few experiments with wires of different diameters will, however, show that this is not the case. This is because the area of cooling surface does not increase at the same rate as the area of section, e.g. if we double the section of a round wire the area of surface is only 1·4 times greater than before.

To ascertain what influence this has on the fusing current we may reason as follows:—When the current is just sufficient

to produce a certain steady temperature, then at that temperature heat must be dissipated at exactly the same rate at which it is produced. The heat is dissipated chiefly by radiation, and the rate of loss of heat per unit length is proportional to the surface area of unit length, and we may write—

$$\text{rate of loss of heat} = K_1 d \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where d is the diameter of the wire, and K_1 is a constant which depends upon the nature of the surface, and upon the difference of temperature between the surface and its surroundings. Again, the rate of generation of heat is proportional to I^2R, where R is the resistance per unit length. But R is inversely proportional to the sectional area, i.e. inversely proportional to the square of the diameter, and we have—

$$\text{rate of generation of heat} = K_2 \times \frac{I^2}{d^2} \quad . \quad . \quad . \quad . \quad (2)$$

where K_2 is a constant depending upon the resistivity of the material. We have, therefore—

$$K_2 \times \frac{I^2}{d^2} = K_1 d,$$

$$\text{or } I^2 = \frac{K_1}{K_2} \times d^3.$$

$$\therefore \quad I = \sqrt{\frac{K_1}{K_2}} \times d^{\frac{3}{2}},$$

$$\text{or } I = m \times d^{\frac{3}{2}}, \text{ where } m = \sqrt{\frac{K_1}{K_2}}.$$

This means that the fusing current is not proportional to d^2, but to $d^{1.5}$.

In practice the index is not found to be so definite as the above argument would appear to show, and it may vary from 1·2 to 1·5 in consequence of minor factors which we have neglected, such as end effects, convection currents, and difficulty of transmission of heat through the material of the fuse. The actual relation between area of section and fusing current for round wires, as determined experimentally, is shown in Figure 187.

The above reasoning applies to all cases in which currents are passed through a series of wires of different diameters, but of the same material, and the same permissible temperature rise, and is at times useful in dealing with the carrying capacities of cables and resistance wires.

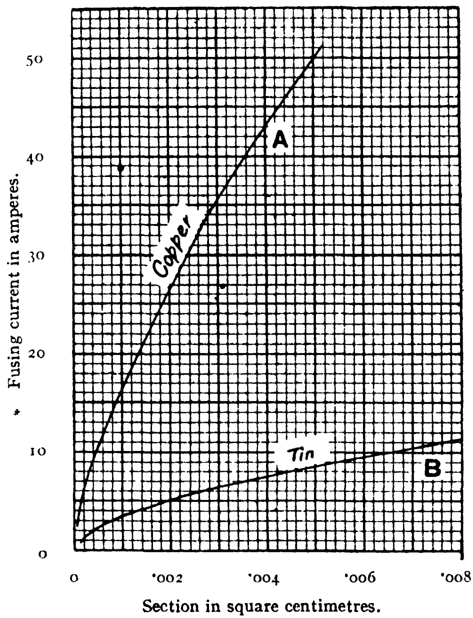


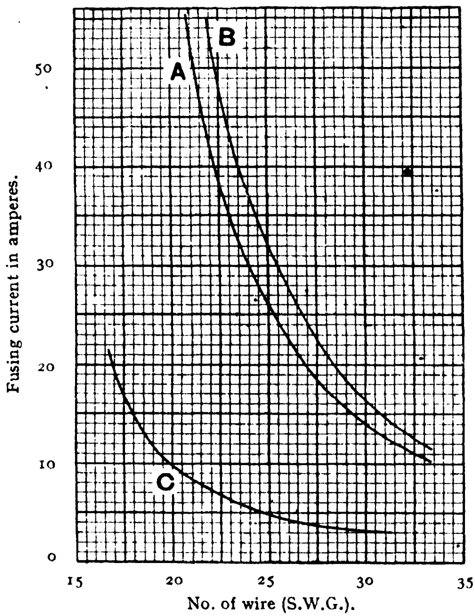
FIG. 187.

For practical purposes it is more convenient to know the fusing current for the various gauges. This is given in Figure 188 for the varying conditions specified underneath. Next in importance to the diameter of a fuse is its length.

When a current is passing through a wire, heat is generated in it, and this heat is continually being dissipated by radiation from the wire and also by conduction along the wire, and obviously the greater the facilities for the dissipation of heat the cooler will the wire be for a given current.

In the case of a long wire the amount of heat conducted

along the wires from points near the centre is very small, whereas in a short wire a considerable quantity of heat is conducted to the terminals from the middle portions of the wire. Owing to the greater facility, therefore, for the dissipation of heat, a short wire, for a given current, will be



A. Copper (long lengths).
B. Copper (in "Damper" type of fuse holder).
C. Tin (long lengths).

FIG. 188.

cooler than a longer wire of the same material and diameter. Therefore to raise a short wire to the temperature necessary for fusion a larger current will be required than in the case of a long wire.

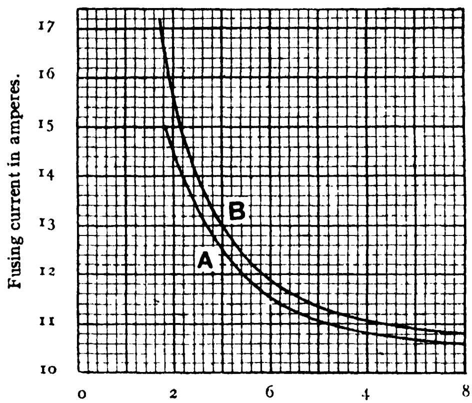
This is easily seen by examining a copper wire carrying a current of suitable strength. The ends of the wire, which are cooled to the greatest extent, are not red-hot, while its centre is glowing brightly.

Hence it is that the fusing current is greatest for short lengths, and diminishes rapidly as length increases, until it would remain constant were it not for the effect of sag due to gravity, etc.

The relation between length and current is shown in Figure 189.

Minor points which will influence fusing current, and which only merit a brief reference are :—

1. The mass of the terminals; for the more massive they



Tinned copper wire, 33 gauge.
A. Mass of terminals = 5 grams.
B. „ „ = 870 „

FIG. 189.

are the greater will be the cooling effect just referred to. This also is shown in Figure 189.

2. The position of the fuse—whether vertical or horizontal. If the latter, and free access of air is allowed, the wire will be kept cooler than when in a vertical position, and the corresponding difference in the fusing current may amount to as much as 8 per cent in the case of thin wires.

3. The environment of the fuse. In some cases the wire stretches free in air from terminal to terminal, whilst in others it is in contact with cold porcelain or other material near its centre. There is no great objection to contact with porcelain,

if it is invariable, but such conditions may increase the fusing current by 30 per cent.

From all this it appears that the correct gauge for fuse wire to be used in a given case cannot be selected merely by reference to some table of fusing currents. Working values should be determined for the particular type of fuse holder which is to be used.

OVERLOAD CAPACITY

One point in connection with fuses, whose importance is often overlooked, is the overload capacity.

If we have a circuit where the full load current is 50 amperes, we do not insert a fuse to blow at 50 amperes, but at some larger current, the percentage overload capacity being defined as—

$$\frac{\text{Fusing current—full-load current}}{\text{Full-load current}} \times 100$$

Thus a fuse for a 50-ampere circuit with a 40 per cent overload capacity should blow at 70 amperes.

It is not desirable that this allowance should be too small, for in that case trouble may be caused by the frequency with which the fuses are blown; on the other hand, if it be too great they may fail to protect the circuit as desired.

The exact allowance will depend very much upon the nature of the circuit. A few typical instances are given below. In actual practice it is often a very rough and ready matter.

Motor circuits from 25 to 75 per cent.

Main house fuses from 20 to 40 per cent.

Sub-circuit house fuses from 50 to 100 per cent.

It must also be pointed out that even if the rated fusing current is passing, the fuse will not "go" instantly, as owing to its heat capacity it will require a certain time depending on the nature of the fuse and holder before it acquires a sufficiently high temperature to ensure its rupture.

The greater the current the shorter this time will be, and under conditions approaching a short circuit it will blow almost instantly.

FUSE HOLDERS

Innumerable patterns exist and the main points to be attended to when choosing a good type are adequate precautions against fire risk, freedom from risks of shocks and burns when fuse replacements are being carried out and convenience in wiring. In the past, and in old installations at the present day, many types of fuses exist which necessitate contact of the hand with metallic portions of the electric circuit when replacements are being made, due to the fuse wire being directly attached to terminals which form a permanent part of the current-carrying conductors. With such arrangements there is always a risk of shock or burns due to attempts being made to insert fuse wires without taking proper precautions to ensure that the circuit is quite " dead." Such types should be regarded as unsuited to modern requirements.

In more modern arrangements a bridge piece, which often takes the form of a tube, of insulating material is employed. This is provided with contacts at each end, which engage with companion contacts connected to the circuit, and replacements are effected by completely detaching this unit from the circuit while the fuse wire is being renewed and thus the risk of shock or burns is materially diminished. This fuse bridge or fuse holder is very commonly made of porcelain, though vulcanised fibre (which is somewhat hygroscopic and liable to char though very tough) is used in some types, and may take any one of a great variety of forms. These forms may be divided into three groups, depending upon the extent to which the fuse wire is enclosed, known as *open types*, *semi-enclosed types*, and *enclosed types* respectively. For heavy duty the enclosed type is undoubtedly the best, though cost of replacement is, as a rule, much higher than in other types.

In open types the fuse is free in air from terminal to terminal and is not surrounded by a tube.

In semi-enclosed patterns the fuse passes through a tube of some insulating non-combustible material, and may touch the holder at one or more points. It is, however, surrounded by air, and free access of air is allowed to the interior of the holder. The addition of a surrounding tube of course prevents to a large extent the flying about of molten metal when the fuse is blown under conditions approaching a short circuit.

In enclosed fuses, the wire is completely encased in a tube, which is filled with some powder, the object being to condense the vapour given off by the hot metal as rapidly as possible. With this type there is practically no risk of hot particles flying about.

Type 1. *Open fuse.* Figure 190.

This pattern, which is now rarely employed, consists of a porcelain bridge piece P, to the two ends of which are secured

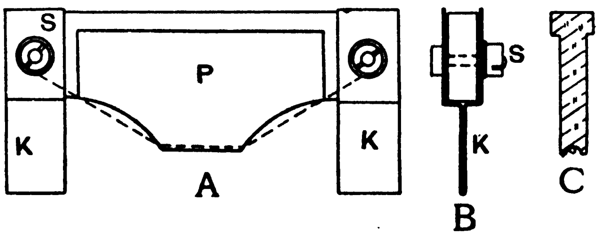


FIG. 190.

by the single screw S the contact pieces K, made out of sheet brass. These fit into suitable clips on the distribution board. The fuse wire is secured at each end by nuts, which are carried by the screws S, and its path is shown by the dotted line. An end view of the fuse is shown at B, and a section through the porcelain at C. This holder is only suitable for currents up to a few amperes.

Type 2. *Semi-enclosed fuse.* Example A, Figure 191, (Plate IX).

This holder, made by the General Electric Co., consists of a porcelain tube A, which carries two brass contact pieces B. These are secured to the porcelain body by the screws C, which pass right through it. The brass contact pieces are prevented from turning round by their peculiar shape, and also by the fact that the screw D, by aid of which the fuse wire is clamped, passes into an indentation in the porcelain body. The fuse wire, which is clamped underneath a nut and washer shown at D, crosses, in its course through the tube, from one side to the other, thus avoiding any contact with the porcelain which might be of a variable nature.

PLATE IX

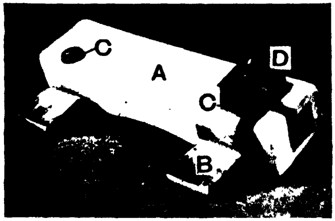
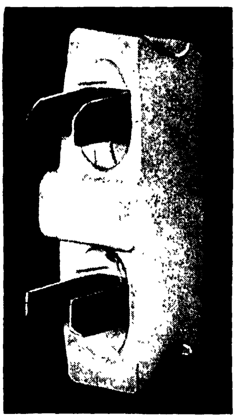


FIG. 191



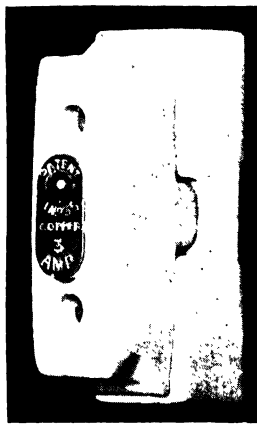


FIG. 193

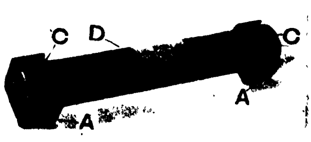


FIG. 194

To face page 286

The fuse holder shown is $4\frac{1}{2}''$ long over all, and is suitable for currents from 10 to 40 or 50 amperes

Example B, Figure 192.

This is the well-known "Damper" type of Messrs. Dorman and Smith. The peculiar shape of the porcelain body P is shown in the figure. The contact pieces B (made of brass) are secured to the porcelain by the screws S, which also carry nuts to clamp the fuse wire. The latter passes through two tunnels in the porcelain body, shown by dotted lines, and near its centre is brought out to the back of the porcelain at O. At this point it is covered over with a circular pad of asbestos which fits into a circular depression D, and is kept in position by the brass plate N, on which is stamped the carrying capacity of the fuse. When the fuse blows, the asbestos pad forms a partition stretching across the path of any arc which might tend to form. The path of the fuse wire is indicated by the chain line. The type shown, which is about one-half full size, represents a holder for use on a distribution board, and is suitable for a 5-ampere circuit.

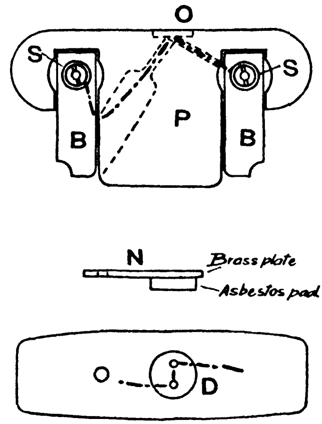


FIG. 192.

Another type of "Damper" fuse is shown in Figure 193, Plate IX. In this case the construction is modified so that no live metal is exposed at the front when the fuse holder is in position, thus satisfying Home Office recommendations on this matter.

Type 3. *Enclosed Fuse.* Figure 194 (Plate IX).

This figure shows the Sachs pattern of enclosed fuse.

It consists of a tube D made of fibrous insulating material to which are riveted two brass end caps C, these in turn being soldered to the contact pieces A, which are made of stamped and bent sheet brass. A small rod is also attached inside each end cap, to which the fuse wire or strip is soldered. The latter

is totally surrounded by a powder, whose chief function appears to be to rapidly cool and condense the vapour set up by the fusion of the metal.

With enclosed types of fuse holders it is often difficult to tell whether the fuse has blown or not, and hence some kind of indicator is desirable.

One such device consists in having a very fine wire in shunt to the main fuse, which in one part of its path passes underneath a label on the outer surface of the tube. Then when the main strip fuses the fine wire also fuses and causes the label to present a charred appearance.

Non-interchangeability of Fuses.—In the past little attention has been paid to the question of preventing the insertion of a wrong size of fuse when effecting a replacement, and difficulties have at times arisen from neglect of this precaution. The usual error is to insert a fuse of too large a current capacity. There is a maximum safe current for each circuit to be protected, and the fuse should be of such size as to prevent this being exceeded. It is therefore important that the holder should be designed in such a way as to make it impossible, when effecting a replacement, to insert a fuse of larger current capacity than is appropriate to the circuit under consideration. (There is no objection, from the point of view of security, to inserting a fuse of *smaller* capacity.)

Again, it is a well-known fact that working difficulties increase rapidly with increase of voltage, and from this point of view it is desirable to make it impossible to use (say) a 100-volt circuit fuse on a 250-volt circuit, although there would be no objection to using a fuse designed for 500 volts on a 250-volt circuit. Precautions of this kind are most important in connection with enclosed fuses.

Summing up, a satisfactory non-interchangeable system of fuse replacement (more especially as regards enclosed fuses) should ensure :—

(1) That it is impossible to insert a fuse of too high a current capacity.

(2) That it is impossible to insert a fuse of too low a voltage capacity.

One of the simplest systems for attaining these ends is

that employed by Siemens Bros. & Co. (to whom we are indebted for information) in their well-known **Zed** type fuses.

The fuse proper is of the completely enclosed type, and comprises a cylindrical porcelain body B (Figure 195), the fuse wire or wires passing through a tubular cavity from end to end. This cavity is packed with a suitable filling and the contact pieces at either end are secured to the body by cement. One of the fixed contacts to which the fuse is connected is in the form of a flat plate P, and the other is ring-shaped as shown at S. These are both secured to the fixed porcelain fitting and are provided with terminal screws. The part K is of porcelain and is lined with metal pressed to form a screw thread round the sides, the current passing from the ring-shaped fixed contact to the thread, and then from the flat top of this part to the upper contact of the fuse cartridge. Non-interchangeability (for current) is secured by the lower contact of the cartridge, which must pass through the gauge ring G before it can come into contact with P. The larger the rated current the larger is the diameter of the gauge ring, and the corresponding cartridge has a lower contact of the necessary diameter.

A fuse of smaller capacity can be inserted, but it impossible to put in a larger one without altering the gauge ring. This can readily be done if necessary with the help of a special tool, which of course should be under the supervision of a competent electrician.

For higher voltages the length of the cartridge is increased (the fixed fittings being suitably modified), so that if a 250-volt fuse is placed in a fitting designed for 500 volts, its shorter length prevents contact being made. Profiles of cartridges for various voltages and currents are shown in the lower portion of Figure 195.

As a rule, fuses are only used on circuits conveying comparatively small power. On switchboards and on large-power circuits they are usually replaced by automatic overload circuit breakers. These, although of much greater first cost, are more convenient in use, and, if of a good type, more reliable and safer in operation.

In concluding our account of fuses, stress may be laid on the fact that the fuse is a very important part of an installation. It is essentially a safety device, and if not efficient may introduce fresh dangers rather than minimise those already

present. It is important that it be of correct size, and in this connection it is well to note that the fusing current of a wire of fixed material and cross-section depends to a large extent on the surroundings, which may easily cause variations of the order of 50 per cent. Thus the fusing current of a wire should always be determined under working conditions.

Again, as previously mentioned, the fuse is a potential source of fire risk. Fire may be caused owing to the presence of the hot wire near to inflammable materials, by the arc set up on fusion, or by the scattering of molten particles (which may possibly be burning).

It is evident therefore that the surroundings of a fuse should be of fireproof material, and every precaution taken to prevent molten particles from flying about.

CONDUCTORS AND CABLES

Before proceeding to discuss the various systems available for distributing the current in a building, it will be advisable to consider the conductors which are available for such purposes, and also the means of insulating them from adjacent conductors.

The most suitable material for a conductor is that which combines the following properties in the greatest degree :—

1. High electrical conductivity.
2. Considerable ductility (i.e. it must be capable of being readily drawn into a wire).
3. Mechanical strength.
4. It must be unaffected by any substances likely to come into contact with it.
5. It must be inexpensive.

Copper is found, on the whole, to fulfil these requirements better than any other substance, though for aerial lines in certain cases aluminium has been adopted by some authorities.[1]

Copper wire intended for cables is usually covered with a thin coating of tin, in order to partially protect it from

[1] As regards the use of aluminium it is found that, for equal conductivities, the diameter and weight of an aluminium conductor are respectively 1·3 and 0·5 of a copper conductor. The aluminium conductor will require, on account of its greater diameter, more insulation and it cannot readily be soldered.

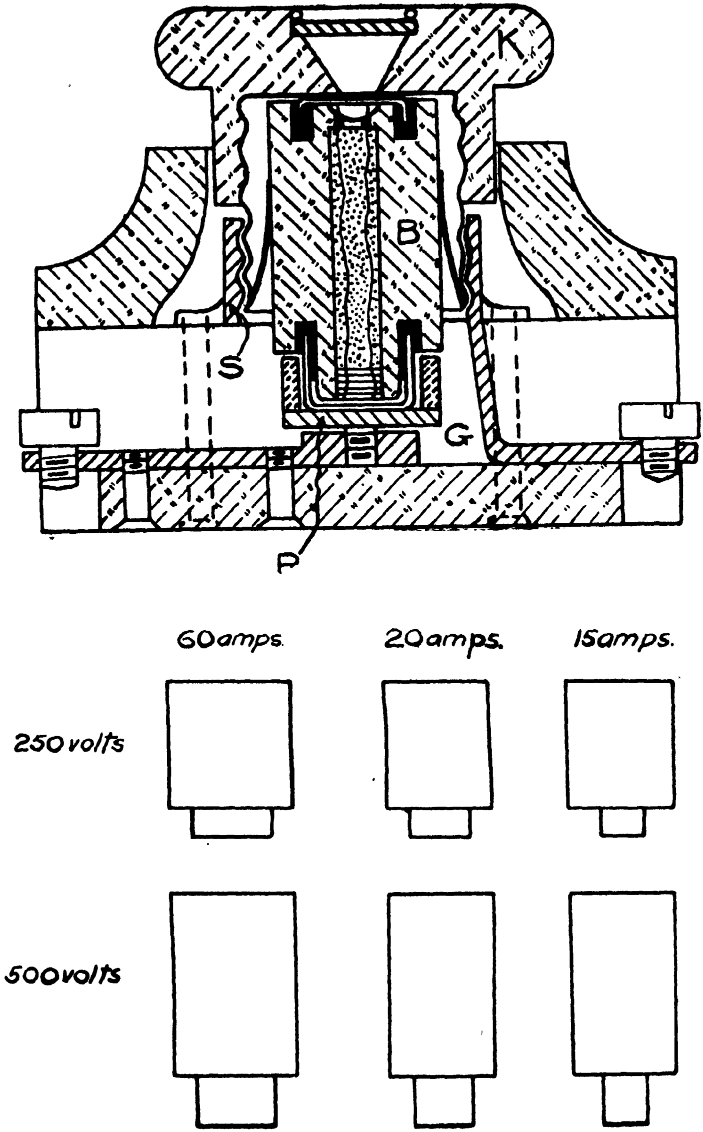


FIG. 195.

the action of the sulphur present in vulcanised rubber. It is inadvisable to use only a single strand on account of the risk of a break occurring, and hence the conductor is usually made up of three or more strands, and is then known as a cable. This not only diminishes the risk of fracture, but also increases the flexibility, a property especially valuable in conductors of large cross-section.

The most commonly used numbers of strands are 3, 7, 19, 37, 61, and 91.

The 7-strand cable is formed by taking one wire as a core and laying the other 6 helically round it, the pitch of the helix being about 14 times the diameter of the cable.

A 19-strand cable is made by laying another 12 strands helically over a 7-strand, the helices in the second layer running in the opposite direction to those in the first layer; and cables containing a still larger number of strands are built up by a repetition of the same process.

To specify a cable it is necessary, therefore, to mention not only the size of wire but also the number of strands. Thus a $\frac{19}{0{\cdot}092}$ cable (spoken as *nineteen nought nine twos*) is composed of 19 strands each 0·092 inch in diameter.

Dealing next with the insulation which is to surround the wire or cable, we may tabulate the desirable properties of such materials as follows :—

1. High insulating properties.
2. Must not be softened or caused to deteriorate by a moderate rise in temperature. (If it does the conductor may become decentralised.)
3. It should not be injured by moisture, sunlight, or access of air; or, if this is not the case, due precautions must be taken to exclude such influences.
4. It should not exert any destructive action on the copper; or, if it does, the latter must first be covered with a protecting layer of some suitable material.
5. It should be impermeable to moisture or be suitably protected.
6. It should possess flexibility.
7. It should be tough and capable of resisting abrasion.

The substances most commonly used for insulating cables

are pure rubber, vulcanised rubber, and impregnated paper. Pure rubber is used to a large extent for insulating flexible cord and it is also used as an inner layer of the insulation on larger cables.

Its expense prohibits its use except in thin layers; and apart from other reasons connected with mechanical strength, in any case it must be protected from air and light, under whose influence it deteriorates somewhat rapidly. It is also readily softened by a rise of temperature.

Vulcanised rubber, which is a compound made by digesting pure rubber with sulphur and various other bodies, is the main insulating material in the majority of cases. It is much more durable than pure rubber, and less affected by a rise in temperature.

The sulphur in it, however, rapidly acts on copper, and if in contact the two substances mutually perish; and hence the latter is protected either by tinning, or by a layer of pure rubber placed beneath the vulcanised rubber. In all good cables both these protective devices are used, for mere tinning, which may be defective in places, is a very inadequate precaution but is extremely useful in preventing a certain obscure oxidising action of copper on pure rubber.

Impregnated paper is also used to a large extent; the copper, which in this case need not be tinned, is wrapped round with a number of layers of specially prepared paper, alternate layers being wound in opposite directions. The paper is then saturated with some preservative and insulating compound, and a tightly-fitting lead sheathing is formed round the cable. It is especially important that there are no openings, however small, in the lead sheathing, as moisture has a very bad effect on this class of cable.

Paper insulated cables are commonly employed for street mains both for medium and high voltages and, when laid directly in the ground, are frequently armoured by a layer of steel wires or tapes, the whole being protected by a tarred jute lapping.

If we now take a piece of typical lighting cable, and examine it at a clean section, the wires will be found to be tinned, and next to them a thin layer of dark pure rubber, as already explained. Then a layer of lighter coloured material will probably be noticed. This is known as a "separator rubber,"

and is a species of vulcanised rubber, containing a comparatively small proportion of sulphur, and above it comes the main insulation of ordinary dark vulcanised rubber. Finally, over all are the tapings and braidings of impregnated

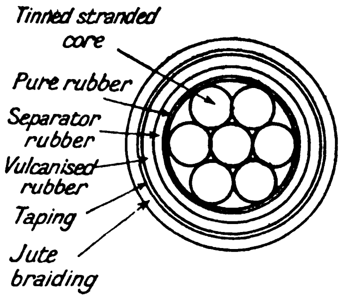


FIG. 196.

cotton and hemp which have no conspicuous insulating virtue, but which act as a mechanical protection and also exclude atmospheric influences to an appreciable extent. This construction is indicated in Figure 196, and in Figure 197 we

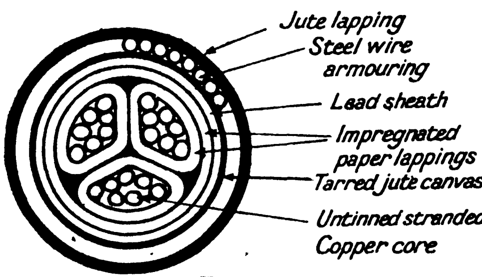


FIG. 197.

have a similar representation of a piece of armoured, lead-covered, paper-insulated cable.

Flexibles for lighting circuits are usually composed of a large number of small wires (for example, 23 wires each 0·0076 inch in diameter) twisted together. The insulation may either be composed of lappings of pure rubber or a moulding of vulcanised rubber.

SCHEMES OF WIRING

As stated elsewhere, the lamps in a house installation are invariably arranged in parallel across the mains.

It is true that occasionally in the case of very large premises the three conductors of a three-wire system are introduced, but even then all the lamps on one side of the system are connected in parallel, so that it will be unnecessary to give this arrangement any special consideration.

We have therefore to consider means of distributing current to a number of lamps in parallel, our chief aim being to keep the drop in the leads small and the voltages applied to the different lamps as nearly equal as possible.

Two distinct arrangements are met with in practice, known as the "tree" and "distribution board" systems respectively. The former is now obsolete, but may still be found in buildings which have been wired a long time, and it will be worth studying briefly and comparing with the latter plan. In the "tree" system two mains are taken into the building and run to what is, electrically, the farthest point, tappings to various lamps or groups of lamps being taken off as required (see Figure 198).

Let us see what are the objections to this method of wiring. In the first place

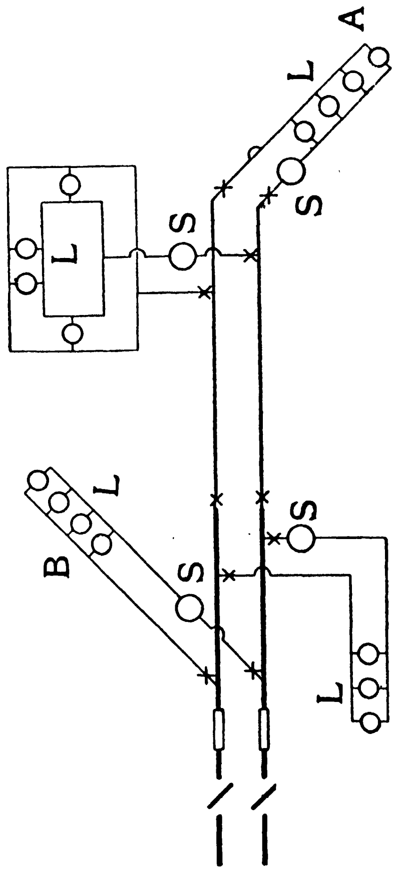


FIG. 198.

we see that the current to lamps at A has to traverse a greater length of lead than for lamps at B, and hence the drop at A will be greater than at B. This is important because a variation in the voltage of, say, 1 per cent may alter the output of a glow lamp by as much as 5 per cent, so that the lamps at A may glow much less brightly than those at B, both being constructed for equal voltages; or conversely, if the former get the correct voltage the latter will be "overrun."

Again, each branch circuit should be protected by a double-pole fuse, and further, these must be grouped together in sight and in accessible positions. Fuses should also be inserted wherever the mains are diminished in section. These conditions necessitate fuses at the points marked with a cross on the diagram, and obviously they can only be grouped together by using a large amount of extra wire. As a matter of fact, they are generally found scattered over the building, and much needless trouble is caused when it becomes necessary to replace one owing to the difficulty of locating it. If a fault occur anywhere, a similar difficulty occurs, because the scheme obviously does not lend itself to ease and rapidity in cutting off parts of the circuit and testing them separately, and finally the arrangement involves making many soldered joints, which always lower the insulation resistance, cost much in labour, and are therefore to be avoided as much as possible. The almost complete elimination of joints is the most marked feature in modern practice, as contrasted with methods in general use some years ago.

THE DISTRIBUTION BOARD SYSTEM

A distribution board itself is only a cluster of branch circuit fuse holders grouped together for convenience, and the principle of the method can in simple cases be carried out without any special board at all. In the "tree" system lamps may be connected to any part of the mains; in this they are supplied only from definite centres, and then only a few are grouped in one sub-circuit, none being connected to the main conductors which carry current to the various parts of the building. In this way joints are largely dispensed with, and a simple and orderly system obtained. The mains

are brought, as shown in Figure 186, through the main fuses meter and switch direct to two small "bus bars" on the

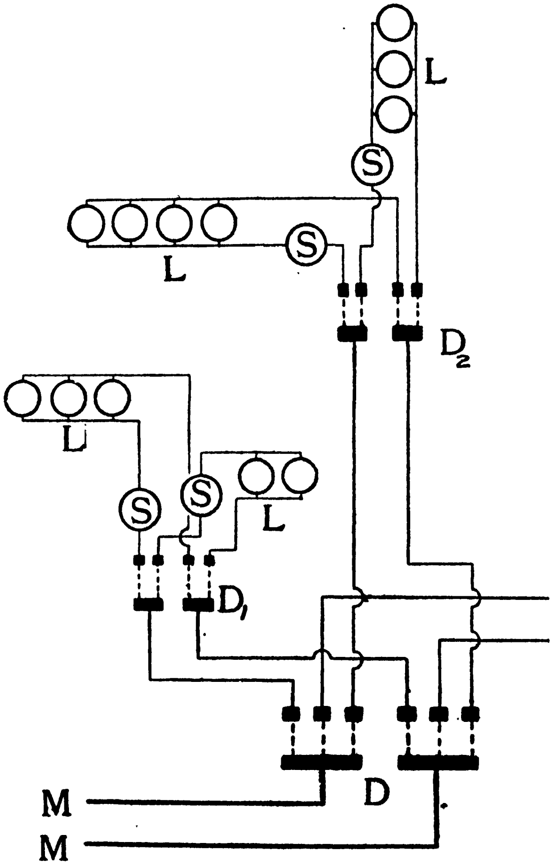


FIG. 199.

distribution board, and a number of lamp circuits are taken off from these bars through double-pole fuses.

In a large building the branch circuits from the main distribution board may not go direct to the lamps, but to sub-distribution boards, which in turn supply the lamp circuits.

These lamp circuits are so arranged that no final sub-circuit carries more than a specified current whose amount is, in practice, to some extent dependent upon the number of "points" on the circuit.

A diagram illustrative of the application of this system in the case of a large installation is shown in Figure 199, where the lamp circuits and switches are labelled L and S respectively, the main distribution board D, and sub-distribution boards D_1 and D_2.

A picture of a distribution board is given in Figure 200;

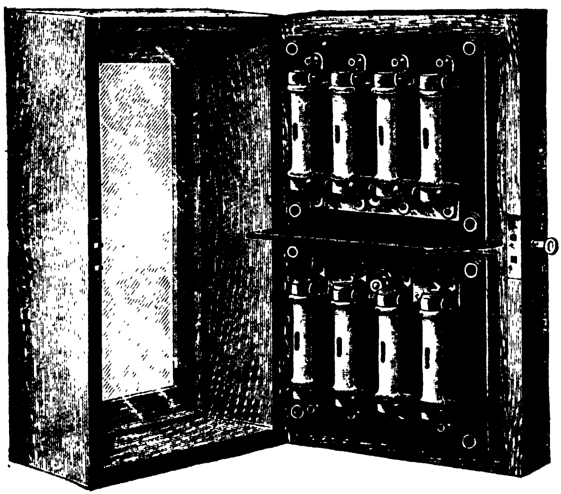


FIG. 200.

in this two slabs of enamelled slate are provided, mounted upon a suitable support, so that the whole can be readily fixed to a wall.

The two slabs, which are separated by an insulating partition, each carry a small bus bar, from which are led off the various lamp circuits, each through a double-pole fuse, the two fuses belonging to any one circuit being arranged in a vertical line with each other. In the example shown, as in all good boards, the fuses are mounted in suitable holders, which are provided with contact pieces at either end, made to

engage with corresponding contacts on the board ; they can thus readily be taken out for the purpose of renewing the fuse wire. The type shown is suitable for a main distribution board, carrying from 25 to 50 amperes per way. The outer case shown in the Figure is made of wood and has a glass front, but it is now more usual to use cases made of iron. The chief advantages of this system as against the " tree " system are :—

1. Uniformity of drop in the various lamp circuits is more asily obtained.
2. Concentration of fuses in accessible positions.
3. Ease of localisation of faults.
4. Small number of joints which are necessary.

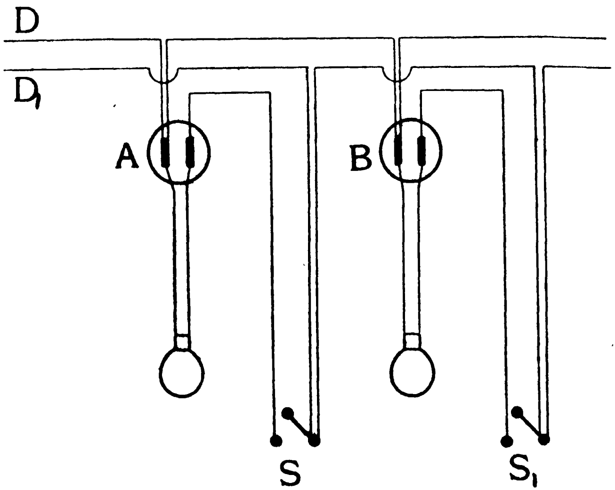


FIG. 201.

As regards the last point, if the " looping-in " method be adopted for wiring the lamp circuits, joints may be completely abolished.

To explain this term, let AB (Figure 201) be the metal terminals of two ceiling roses shown diagrammatically for clearness, each carrying a lamp, controlled by its own switch S S_1 ; and let D D_1 be the origin of the circuit at the distribution board.

Then if the wire from D dips into all the ceiling roses, and that from D_1 into all the switches, the fittings may be wired without making any soldered joints at all. These conductors need not necessarily be cut, for the wire may be bent and a portion bared to enter each fitting, as at A in Figure 202. In practice, however, it is often more convenient to cut the wire, and if so some little care must be taken to ensure a good contact, for if the two ends are secured by the screw of the fitting, as shown at B, there is a risk of a loose contact occurring which would cause much heating at this point, and hence it is more satisfactory to solder the two ends together. This operation, although it involves soldering, is much simpler and demands much less skill and time than does the making of an ordinary soldered and insulated joint. "Looping in" is now an almost universal practice, although it requires the use of an extra amount of cable, for every joint avoided not only reduces the labour of wiring, but also eliminates a possible source of trouble.

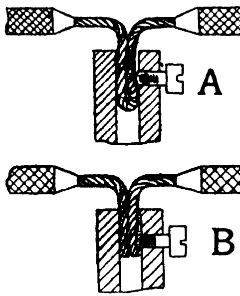


FIG. 202.

CARRYING CAPACITY OF CABLES

When deciding what magnitude of current may be passed through a cable of given size, or, alternatively, choosing the size of cable to carry a given current, it is necessary to examine the question from several points of view and the various aspects of the matter are dealt with below.

(1) *The Heating of the Cable.*—The insulating materials used in cable construction can only stand a very moderate temperature rise without being adversely affected (the values allowed are 11·1° C for vulcanised rubber and 27·7° C for paper), and, when current flows through a cable, a certain power is wasted in the copper which causes a temperature rise whose permissible value is limited by its effect on the insulation. In the past a current density of 1000 amperes per square inch has been looked upon as a safe limit, from the point of view of heating, for cables insulated with vulcanised rubber, but,

as a matter of fact, constant current density in cables of various sizes does not result in uniformity of temperature rise. For example, if we consider the effect of doubling the diameter of a cable we find that the area of cross-section and the carrying capacity (on the basis of constant current density) will be quadrupled while the resistance will be reduced to one-fourth of that of the smaller cable. This will result in quadrupling the rate of heat production (since this varies as I^2R) while the radiating surface of the cable core is only doubled, thus giving a higher temperature rise.[1]

The best criterion of the size of cable from the point of view of heating (so far as circuits for light and power are concerned) is the Wiring Table of the Institution of Electrical Engineers which is founded on the results of careful tests. If this table is examined it will be found that current densities of much higher values than 1000 amperes per square inch are allowable (from the heating point of view) in small cables, while in large cables the current densities must be kept below 1000 amperes per square inch if the standard value of temperature rise is not to be exceeded. It will also be noted that the carrying capacity of a cable insulated with paper is greater than if insulated with vulcanised rubber, this being due to the greater temperature rise to which paper may be subjected without risk of deterioration.

(2) *The Voltage Drop in the Cable.*—When current is sent through a cable there will always be a loss of voltage in the cable. In many cases this will be strictly limited to a magnitude of a very few volts by the conditions of the circuit, and it will be necessary to employ a cable of such a section that the product of the resistance of the cable into the current

[1] The theory concerning current and diameter given as applying to fuses on page 280 may also be applied to other cases of circular conductors of various diameters when the temperature rise is constant as, for examples, to resistance wires and to insulated conductors.

Another interesting point concerning current-carrying conductors is the connection between current capacity and temperature rise, other factors being constant. When a conductor has reached a steady temperature, the rate of generation of heat and the rate of dissipation of heat will be equal. The former is proportional to I^2 and the latter to the temperature rise (θ) and we may write $I^2 \propto \theta$ or $I \propto \sqrt{\theta}$. We see that doubling the current in a conductor quadruples the temperature rise if other factors remain constant.

through the cable will give a value falling within the required limit. The voltage drop in a cable is very important where long cables are concerned, and will often necessitate the use of a cable which is much larger than is needed to fulfil temperature rise conditions. On the other hand, when short lengths of cable are concerned, the voltage drop will be small and the heating limit will be the more difficult to satisfy. It will be realised that in each case we have two distinct limits to the carrying capacity of a cable and the area of cross-section used must be large enough to satisfy both requirements.

As a concrete example, consider the transmission of a current of 65 amperes through a V.I.R. cable over various distances, the voltage drop allowable being 8. Reference to the I.E.E. Wiring Table shows that a cable having an area of cross-section of 0·04 sq. in. will be required to satisfy the heating limit and a little thought will show that, from this point of view, the area of section will be independent of the length of the cable. These facts are incorporated in the graph shown by the continuous line in Figure 203.

As regards the area of cross-section from the point of view of voltage drop, the permissible resistance of the cable will be $\frac{8}{65}=0{\cdot}123$ ohm and this value will be independent of the length of the transmission. If this length is assumed to be 200 yards the area of cross-section of the cable will be given by the formula

$$A=\frac{L\rho}{R}=\frac{200\times 2\times 36\times 0{\cdot}00000068}{0{\cdot}123}=0{\cdot}0796 \text{ sq. in.}$$

(The length of the cable will be twice the distance of transmission.) If the length of the transmission is altered the area of section will be altered in proportion and is shown for various lengths of transmission by the dotted line in Figure 203.

The minimum area of section in any case, which will satisfy *both* conditions, is shown by the thickened portions of the graphs.

(3) *The most economical area of Section of the Cable.*—There is still another point of view, which may be termed the financial point of view, from which the choice of section of a cable may be considered. It is not necessary in this book

to go deeply into the matter, but the main facts are important, the more so since similar problems occur in other branches of engineering. Consider the case of a fairly long feeder cable (it is in connection with such cables that the financial point of view is of particular importance), it is clear that the total annual charges incurred on account of the cable may be divided into two groups, (*a*) the annual running costs which will consist of the cost of the energy wasted in the cable during the year, and (*b*) the annual fixed costs which comprise the annual sinking fund and interest charges on the sum of money

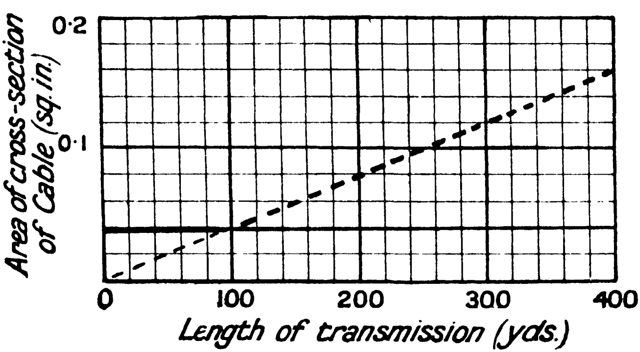


FIG. 203.

involved in the purchase and laying of the cable. It will be seen that, for a certain current, the larger we take the area of section of the cable the less will be the resistance and the less will be the annual value of the energy lost in the cable. On the other hand, the greater the area of section, the greater will be the first cost involved and the greater will be the fixed annual charge. These facts are shown in a general way in Figure 204, and if, for each area of section of cable, we ascertain the total annual charge, which will be the sum of the appropriate annual fixed and annual running charges, we shall find that this quantity has a well-defined minimum value for a certain area of section, and this will give the best size of cable to use from the point of view of economy. Of course this area of section may not be large enough to fulfil

the two technical requirements described above, and if so it must be disregarded as a solution of the problem (the technical requirements *must* be fulfilled). If, however, the most economical area of section is large enough to meet the technical requirements, it should be looked on as the most desirable section to employ. It is of interest to note that the graph of

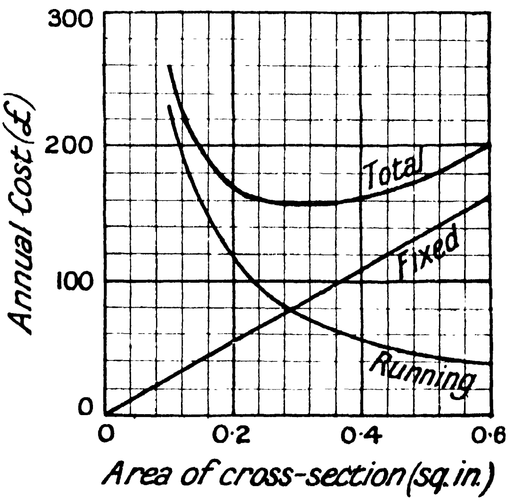


FIG. 204.

the total annual cost is usually flat near its lowest value, which means that a reasonable departure from what is theoretically the most economical section will not greatly affect the magnitude of the total cost.

The particulars of the case illustrated are as follows :—

Current, 200 amperes.
Cost of copper in form of cable, £300 per ton.
Cost of energy wasted in cable, 0·75 penny per B.O.T. unit.
Annual allowance for interest and depreciation, 10 per cent.
Hours per year during which cables are used, 4380.
Length of cable used in calculation, 1 mile.

SWITCHES

Before describing or illustrating any actual types, it will be as well to enumerate the various points which are essential in all good forms ; these are as follows :—

1. The area of contact and the area of section of the conducting portion must be so large that no undue heating may occur.

The current density permissible in the conducting portion may be taken to be from 1000 to 1200 amperes per square inch if of copper, and 600 or 700 amperes per square inch if of brass. Of course it may be found necessary to make portions of a switch of larger section than required by the above rule on account of mechanical considerations.

The current density at the point of contact will depend to a very large extent upon the nature of the contact, which should be arranged so as to be " springy " and not rigid and unyielding.

Three typical forms are shown in Figure 205, in which figure, it may be mentioned, no attempt is made to indicate the manner in which current is conveyed to the contact.

In type A a suitable current density may be taken as about 100 amperes per square inch. Simple contacts of this kind may be met with in small switches used for a few amperes ; an example in a larger switch is shown in Figure 206.

In type B the contact is improved by bending over the fixed portion and by the addition of saw cuts, thus increasing the springiness. The current density in this type may be taken as about 150 amperes per square inch ; it is a type much used in small lighting switches. It is also frequently used for main switches.

In type C one contact is made of a series of copper strips or laminations.

It is immaterial whether the fixed or moving contact be laminated, though the latter case is more usual. A suitable current density is from 200 to 250 amperes per square inch of actual contact. In this type it is desirable that distance pieces be inserted at intervals between the laminations. This increases the springiness and improves the ventilation. This form of contact is very suitable for main switches, and is practically the only type used for very large currents.

2. The length of break should be so large that there is no risk of an arc being maintained even when the switch is

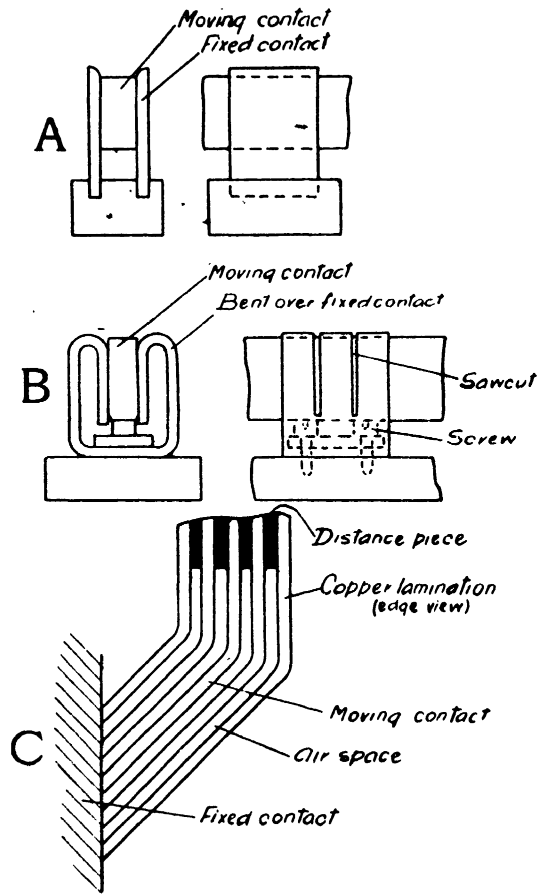


FIG. 205.

operated at currents and voltages appreciably in excess of its rated values.

If the switch is a double-pole one, the two poles should preferably be separated by an insulating partition.

3. The moving portion of the switch should be provided with a spring in order that the final break may be quick, irrespective of the rate at which the handle is moved by the operator. It is also desirable (more especially in small switches) that when the handle is not held in any way there should be either good contact or none at all (i.e. it should be impossible for the two contacts to remain just touching each other). For large main switches, instead of arranging that the circuit is broken quickly on the main contacts, auxiliary

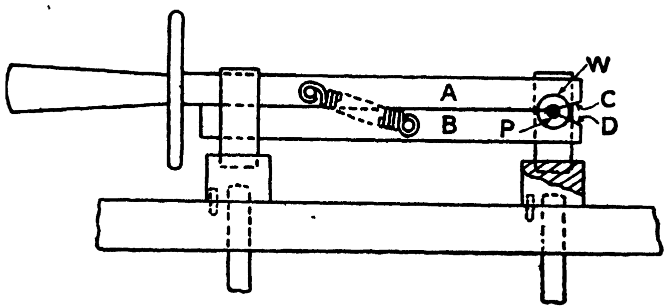


FIG. 206.

contacts may be provided to break the circuit finally and quickly.

The object of providing a quick break is to prevent inexperienced operators separating the contacts slowly, which would allow time for the resulting arc to damage the metal parts.

4. The switch should be provided with what is known as "positive action." That is to say, when a spring is used to provide the quick break it should not also be depended on to overcome the friction of the contacts (which might be unduly high, so ultimately causing permanent distortion of the spring). Actual methods for securing "positive action" are described later.

5. It is often desirable that a switch be provided with a quick "make" in addition to a quick "break." This is an additional safeguard against inexperienced (or evilly disposed) operators causing burning of the contacts.

6. The handle and cover should either be of insulating,

non-hygroscopic and incombustible material, or of metal insulated from all working parts. In many situations when these parts are of metal it is also necessary that they be earthed.

7. The base must be of insulating, non-hygroscopic and incombustible material. Porcelain, enamelled slate, or marble are the materials commonly employed.

8. All parts should have adequate mechanical strength.

9. Convenient means should be arranged for attaching the current carrying leads.

The examples of switches which are described below have been chosen with a view to indicating how items 3, 4, and 5 in the above list may be secured. The same ends may be attained in other ways, and students are advised to carefully examine the action of such modern switches as come under their notice.

An interesting method of securing quick break and positive action in a knife switch of considerable capacity is shown in Figure 206. The blade is in two parts, A and B, which are held together by a steel washer W countersunk into the material of the blades. The handle is rigidly attached to the part A, while part B is attached to part A by means of the spring shown. The switch is of the single pole, single break type, one of the contacts also serving as a hinge, the blades pivoting round the hinge pin P, which passes through holes in the fixed contacts. When the handle is operated so as to open the switch, the part A of the blade is withdrawn from the front contacts and the spring connecting it to part B extended. It will be noticed in the diagram that the heels of the two parts of the blade are cut away and, after a suitable amount of motion of the part A of the blade, the portions of the blade marked C and D engage with each other and the part B of the blade is pulled out of the fixed contact by the positive action so secured. After the friction of the contact has been overcome the spring connecting the two parts of the blade gives the desired quick break. In this type of switch the current is conveyed to the fixed contacts by bolts passing through the insulating base. These bolts also serve to secure the contacts to the base, a steady pin being fitted to prevent any twisting round of the contact.

Another very good type of main switch, made by Messrs.

Berry, Skinner & Co. (to whom we are indebted for information), is shown in Figure 207. There are several novel features about this switch and it is practically fool-proof. The figure shows a vertical section through the centre line of a D.P. switch, this section passing through the handle, springs, etc.

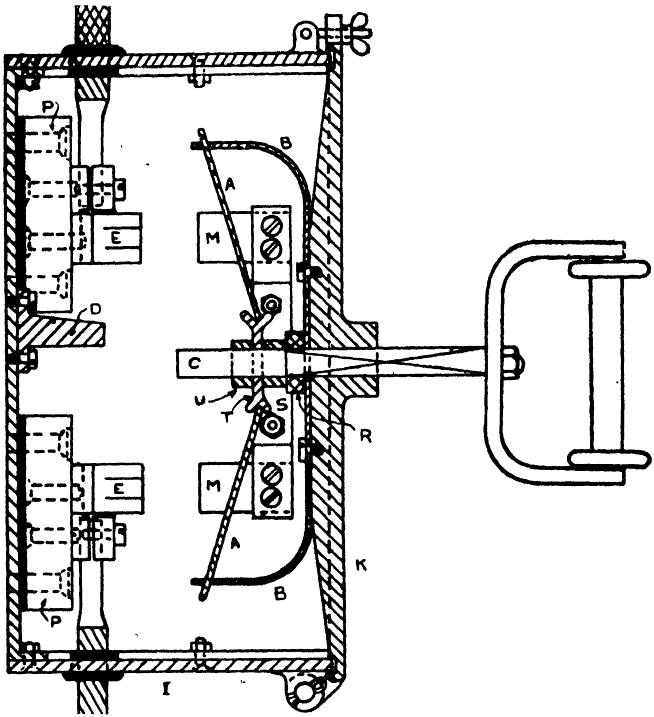


FIG. 207.

Only one pole is shown in the figure, the other being removed owing to the plane in which the section is taken. The poles are separated from each other, and the sides of the case shielded by stout boards of fireproof and insulating material. In the first place it should be noted that the switch is provided with both a quick *make* and a quick *break*. To close the switch the handle is pushed in and the first part of this movement

brings the bars AA into a vertical position, thus distorting the spring BB, which up to this point has resisted the motion. Beyond this point the ends of the spring again approach each other, and its tension assists the force exerted by the hand instead of opposing the latter. This sudden change from opposition to assistance ensures a quick *make*, and evidently, when the switch is opened, it will be equally effective in giving a quick *break*. There are but two positions in which the blades will stop naturally—" full on " or " full off."

When the switch is closed the rod C lies immediately under the projection D, thus resisting any attempt to open the cover. When the switch is open, C is no longer under D and the cover may be removed.

Again, should the cover be open and the moving contacts in the position for closed circuit, it is impossible either to close the cover or to make contact, because the rod C then projects sufficiently to touch D, thus preventing any closer approach of the fixed and moving contacts.

In order to liberate space for more important matters, descriptions of small lighting switches, the many types of lighting fittings, and systems of wiring have been omitted from the present edition. For information on such matters readers are referred to books dealing with actual installation work.

APPENDIX I TO CHAPTER XII

METHODS OF CHARGING FOR ELECTRICAL ENERGY

The methods used for charging for electrical energy differ considerably from the methods used for charging for other forms of energy, as, for example, when energy is supplied in the form of gas. This is due to the special conditions under which electrical energy is generated. In the case of gas it is found to be a simple matter to store the product economically and thus the generating appliances, when in use, can be worked at full output, which leads to economical production. Electrical energy, on the other hand, cannot be stored in bulk with simplicity or economy and it is, generally speaking, generated at a rate sufficient to meet the requirements at the moment. It follows, therefore, that electrical energy is often being generated under conditions which are far from being the most efficient for the plant concerned, and this state of affairs is reflected in the systems usually used for charging for electrical supply. The price charged for electrical energy must be such as to cover the entire costs of generation and distribution and it will be well therefore to consider briefly the factors affecting the costs of production.

Consider a small generating station; in order that this station may be in a position to give an electrical supply, considerable expenditure of money must be made on plant, buildings and cables, and certain annual costs will be incurred on account of interest and sinking fund charges in connection with this expenditure. For a certain station these charges, which may be termed the annual fixed charges, will not be directly dependent on the number of units turned out per annum by the station.

In addition, when the station is generating energy, certain annual costs will be incurred for fuel, oil, water, stores, and wages. These may be termed the annual running costs and their total will be roughly proportional to the number of units turned out per annum.

In practice, of course, the matter is not quite so simple as is outlined above; it is, for example, difficult to allocate some of the charges as between fixed and running costs. Thus a portion of the annual bill for wages and salaries may properly be regarded

as an annual fixed cost, and the same remark applies to a small portion of the cost of fuel. For our purpose, however, the rather crude division of costs indicated above will suffice and undue elaboration is not desirable. Figure 208 shows the annual costs of running a small station plotted against the number of units turned out per annum. A continuous line shows the annual fixed costs while a dotted line indicates the annual running costs. The chain line shows the total annual costs and these, while increasing with the number of units turned out per annum, do not increase proportionately with that quantity. The important

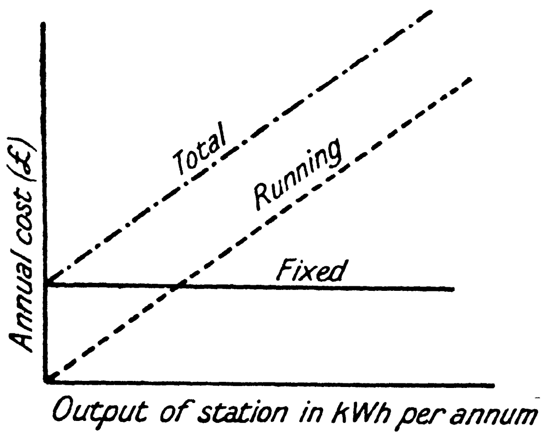


FIG. 208.

point to be realised is, however, perhaps brought out in a more striking manner in Figure 209 where the ordinates represent the average cost per unit generated instead of the total cost of running the station as in the previous Figure. Here we see that the running cost per unit, represented by the dotted line, is independent of the number of units turned out per annum by the station, while the fixed cost per unit, represented by the continuous line, is less the greater number of units turned out (due to the fact that the total annual cost is divided over a greater number of units as the annual output increases). The total average cost per unit is shown by the chain line, and it will be realised that in order that this cost may be low it is necessary that a station should turn out a large number of units per annum in proportion to its maximum capacity. We express this fact by saying that in order that the average total cost per unit of a station may be

low the station must have a high load factor. Load factor has been defined in slightly different ways by different authorities, but essentially it is the ratio of the average load on the station to the maximum load which the station can supply. In the diagrams generating costs only have been taken into account, but the position is much the same in regard to the costs of distribution which have also to be covered by the charge made to the consumers. Now when a consumer is connected to a supply system he must be debited each year with a due proportion

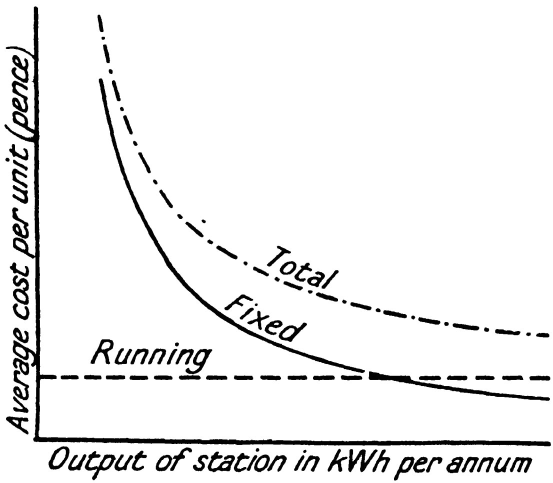


FIG. 209.

of fixed costs (depending upon the maximum demand for power which he makes on the station) and, in addition, he must be debited with a due share of running costs which will be dependent upon the number of units he takes per annum. It will be clear, therefore, from what has been said in connection with the total costs of the station as a whole, that the greater the number of units a consumer takes per annum in relation to his maximum demand for power, the lower should be the average cost per unit and an equitable system of charging should give this result. A consumer using energy for many hours per day (he may be called a long-hour consumer) is likely to have a good individual load factor and, in general, he should be charged a lower average price per unit than a consumer using energy for only a few hours

per day (a short-hour consumer) who is likely to have a low individual load factor. When energy is charged for at a flat rate per unit (corresponding to the system used when energy is taken in the form of gas), the system is clearly unfair to the long-hour consumer with a good load factor. The system briefly described below is one modern example of the methods used to correctly incident the charges on various classes of consumers. Other somewhat similar schemes are also in satisfactory operation.

THE MAXIMUM DEMAND SYSTEM

In this system the circuit of the consumer is fitted with a meter to record the number of units used and also with a maximum demand indicator which is an instrument devised to indicate the maximum power demand made by the consumer in the period over which the charge is being considered. This instrument is sluggish in action so that it largely ignores excessive demands lasting for only a few minutes. This prevents the consumer being unduly penalised for temporary indiscretions in the use of too many of the electrical appliances at his disposal at one time.

The maximum demand meter may be read several times during the half-year and re-set after each reading, the average value of the maximum demand being used for assessment purposes.

The readings of the meters having been taken, the customer is charged at a high rate per unit (say, sevenpence) for the number of units corresponding to the daily use for one hour of the maximum demand, plus a low rate per unit (say, one penny) for all units used in excess of that number. The high rate per unit is designed to cover all the fixed cost appropriate to the particular consumer together with the running cost of the units charged for at the high rate. The low rate for additional units is designed to cover running costs only. An example of the operation of this system for a consumer having a maximum demand of one kilowatt is given in the table below, the two rates of charge being those mentioned above.

Total units used per annum.	Number of units at seven-pence.	Number of units at one penny.	Cost of units at seven-pence.	Cost of units at one penny.	Total cost.	Average price per unit.
			pence	pence	pence	pence
400	365	35	2555	35	2590	6·475
800	365	435	2555	435	2990	3·737
1200	365	835	2555	835	3390	2·825
1600	365	1235	2555	1235	3790	2·369

In another system, much used for domestic supply, the total bill is made up of a certain percentage of the rateable value of the house concerned (the figure being designed to cover the probable fixed costs of the customer) plus a small charge per unit of energy consumed. As an example, the total charge may be made up of 20 per cent of the rateable value plus one penny per unit. The effect of the load factor of the consumer on the average price per unit will be much the same as in the system already described.

Consideration of the principles outlined above will enable readers to understand other points which arise in connection with costs of electrical energy, such as the low figure often charged for energy used for motors (usually a long-hour load) and the possibility of obtaining energy at cheap rates at such times as the load on the station concerned is small.

APPENDIX II TO CHAPTER XII

METHODS OF SUPPLYING POWER TO LAMPS

Theoretically speaking, power may be supplied to a number of lamps in two distinct ways: at constant current and at constant voltage. In the former case all the lamps would be in series and the current would be the same at every point in the circuit, so that the generator would have to supply an unvarying number of amperes at a voltage which automatically adjusted itself to the number of lamps in use at a given instant. In the latter case the voltage is kept constant between supply mains which may branch out into innumerable side paths, the lamps being connected in parallel across them. This is the arrangement assumed so far in this book.

It is scarcely necessary to discuss at length the working details required in the first case, because (although it was tried in the early days of electric lighting) one or two fundamental difficulties make it impossible in practice, at any rate for incandescent lamps. In Chapter III, page 47, a question has been worked out to illustrate this, from which it will be seen that to light even a village in this way would require a P.D. between the terminals of the generator of enormous magnitude, a single house supplied with, say, twenty 100-volt lamps, having a voltage of 2000 across its supply mains. Such a system would be dangerous in the extreme, apart from other considerations.

It may of course be argued that our ordinary lamps are naturally

unsuited for the purpose, and that special low voltage lamps could be made for use on series circuits, such as, for instance, a 60-watt lamp taking 6 amperes at 10 volts. This was tried years age, but such a construction is unsatisfactory, especially for lamps of small candle-power, and even if good lamps of the kind could be made, the line and generator voltage would still be so high as to be impracticable. Hence all incandescent lighting is done on the parallel system, although of course a few lamps may be put in series when it is convenient to do so, as in street-car lighting where five 100-volt lamps can be run from the 500-volt supply.

In one limited field of usefulness, however, constant current series lighting was used with great success for many years, and has not long died out. This was in connection with arc lamps. When a large, but still limited, number of such lamps had to be supplied, there were certain advantages gained by putting them all in series, and machines of special type were made to run as many as sixty such lamps, each taking, say, 10 amperes at 50 volts, the generator giving 10 amperes at 3000 volts on full load. But this very success shows clearly the unsuitability of the system for general purposes. It would be evidently impracticable to run all the arc lights of an average town from one large generator, as might easily be done on the parallel system.

In one respect only, a series system of supply would be a distinct advantage. It would immensely reduce the losses on the distributing mains, or, with the same percentage loss, the capital invested in copper, and although primarily only beneficial to the supply company, would of course in the end benefit the consumer.

In parallel systems the same rule holds good. If the working voltage be doubled, the copper required is reduced to one-fourth for a given percentage loss in the mains. Of course better insulation is required, but that is cheaper than copper.

Hence the tendency has always been to increase the voltage on distributing systems, and it is only limited by considerations of safety and the possibility of obtaining incandescent lamps to work at that voltage. In this country the Board of Trade regulations prohibit voltages greater than 250 in ordinary buildings, and 230 volts is now a very commonly used value. There is little prospect of a further rise in the voltage of supply.

THREE-WIRE SYSTEM

The three-wire system, which has been in general use for many years on all direct current supply circuits of any magnitude, is a method by which power can be distributed at double the working voltage used on the lamps. Three mains are used ; (1) the positive

and negative " outers " between which the voltage is maintained at some steady value, usually from 400 to 500 volts ; (2) the " middle " or " neutral " wire, which is kept at a potential midway between them by automatic regulating appliances at the generating station. Tappings from the middle wire and from one of the outers are taken into a building and the circuit arrangements made there as usual, using 200 to 250-volt lamps. As far as possible the system is " balanced " by distributing the consumers equally between the two sides of the network, and in a large building all three conductors may be introduced, when the wiring is split up into two distinct and well-insulated systems, each supplied by one of the outers and the middle wire.

Figure 210 I shows conventionally such an arrangement, but without any station connection to the middle conductor, which therefore becomes merely a convenience in wiring. If the loads are always equal this will be satisfactory, but if otherwise the voltages will no longer be the same on the two sides of the system, although the sum of the two will be constant and equal to 440 volts in the case shown.

To illustrate this, consider the simple case shown in the diagram, and for convenience assume each lamp takes $\frac{1}{3}$ ampere at 220 volts. This means each lamp has a working resistance of 660 ohms, and therefore the total resistance of the four lamps at C is $\frac{660}{4} = 165$ ohms, and that of the three lamps at D is $\frac{660}{3} = 220$ ohms ;

$$\therefore \text{ resistance in circuit} = 165 + 220 = 385 \text{ ohms,}$$

and the current, which is necessarily the same all round the circuit, will be $\frac{440}{385} = \frac{8}{7}$ ampere.

$$\begin{aligned} \therefore \text{ P.D. across C is } & \tfrac{8}{7} \times 165 = 188\tfrac{4}{7} \text{ volts.} \\ \text{P.D. ,, D is } & \tfrac{8}{7} \times 220 = 251\tfrac{3}{7} \text{ volts.} \\ & \overline{\underline{\underline{440 \text{ volts.}}}} \end{aligned}$$

Hence the lamps at C will be very dim, and those at D will be much overrun. If the grouping be changed to that shown in II, the current will be unaltered, but the higher voltage will now be across C 1, and the lower across D 1.

In practice the middle wire would be connected to some form of " balancer," which is frequently a couple of similar machines on the same shaft, whose function it is to keep the voltages equal in spite of inequality of loads on the two sides of the system. This is shown diagrammatically in II ; but at present it is not desirable to discuss its action. The main point is that the currents are no longer necessarily the same on the two sides of the system,

and that the middle wire now carries the difference, which is towards the station in I, and away from it in II.

With reasonable care in arranging the load, this current will never be very great compared with that in the outers, and hence the middle wire can be made of smaller section, usually one-half that of the outers, but this depends partly on the nature of the load.

Such a system at 440 volts will require much less copper than a two-wire system at 220 volts to supply the same total power

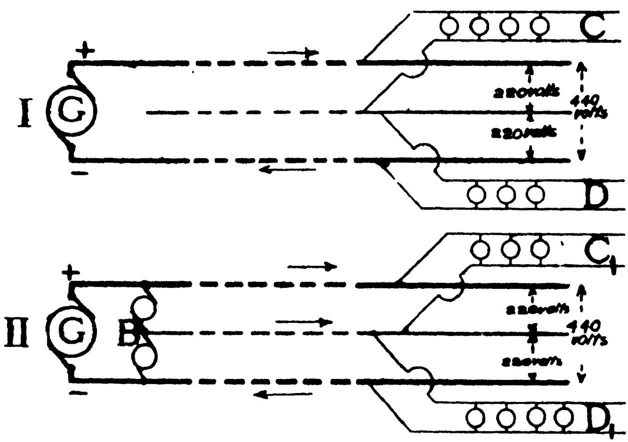


FIG. 210.

with the same loss, for the current in the outers will only be one-half as great; and as the losses vary directly as the square of the current, the section of the outers need only be one-quarter as great as in a two-wire system.

If therefore in the two-wire system we need two wires each of a certain cross-section which we can take as unity, in the three-wire system we need two wires each of section $\frac{1}{4}$, and a third section $\frac{1}{8}$; so that the total amounts of copper are to each other in the ratio

$$1+1 : \tfrac{1}{4}+\tfrac{1}{4}+\tfrac{1}{8} \quad \text{or} \quad 1 : \tfrac{5}{16}.$$

This simple calculation does not take all the factors into account, but it is sufficient to show the advantage of the method.

It will be noticed that the current density in the outers has been doubled, as compared with the two-wire system. Even if this be kept the same, there will be a saving in copper, although not

so much, but it may be pointed out that there is no objection to increasing the current density providing the heating limit is not reached, and in long distributing mains the energy loss becomes important before that limit is approached. With short runs the case is different, and hence, whether it is permissible to double the current density or not, will depend upon the circumstances. An example will make this clear.

Assume power to be supplied at the far end of a supply main of total length 1 mile, and which for convenience we will suppose has 1 square inch sectional area. The voltage is to be 220, and the loss must not be more than 5 per cent of the power delivered.

First applying the formula

$$R = \frac{\text{length in inches}}{\text{area in square inches}} \times \frac{0{\cdot}66}{10^6}$$

we find the resistance of the main to be 0·042 ohm.

Let I = current which satisfies the given conditions,

$$\text{then power delivered} = VI = 220 \times I$$

$$\text{,, lost} = I^2R = I^2 \times 0{\cdot}042$$

$$\text{and } I^2 \times 0{\cdot}042 = \tfrac{5}{100} \times 220 \times I$$

$$\therefore\ I = \frac{5 \times 220}{100 \times 0{\cdot}042} = 262 \text{ amperes.}$$

If the current exceeds this value the loss will be more than 5 per cent of the power delivered, and vice versa.

Evidently in this case there would be no objection to doubling the current density, and much economy in doing so.

Now suppose the original length of main was only $\frac{1}{5}$ mile. Then its resistance would be $\frac{0{\cdot}042}{5} = 0{\cdot}0084$ ohm. And by the same argument the current giving 5 per cent would be $5 \times 262 = 1310$ amperes.

In this case it would not be desirable to double the current density, except in very special circumstances.

It is obvious that the principle embodied in the three-wire system may be extended to any number of groups of conductors, and in practice a "five-wire" system has been actually used at Manchester and elsewhere; but the increasing complexity of the circuits is such a drawback that such instances are very exceptional.

In Figure 210 the current is shown supplied directly into the mains. This is merely for convenience; in practice the current would be fed into the system at various tapping points by means of special cables known as "feeders." A feeder differs from a

supply main in the respect that no load connections are made to it. On the supply mains the voltage must be kept as nearly as possible constant at all points, but the voltage at the station end of a pair of long feeders may be considerably above that value.

The middle wire of a three-wire system is always earthed at the generating station, usually through a recording ammeter. This is an important precaution, because it ensures that the potential above earth on any consumer's fittings shall never more than slightly exceed the voltage of supply. If all three wires were insulated, and an earth occurred on one of the outers, the other outer would (taking values used in previous examples) at once become 440 volts above the earth, and the middle wire 220 volts above earth; and hence, although the P.D. between the two wires themselves would be only 220 volts, it would be possible for an uninsulated person to obtain a 440-volt shock by accidentally touching any "live" fittings connected to the outer.

CHAPTER XIII

LAMPS

A SATISFACTORY source of light should produce in an economical manner those ether waves which are visually most effective. It is not merely a question of the intensity or the strength of the waves. Our eyes have been developed under the influence of sunlight, and the more closely the visible radiation from an artificial source approaches sunlight in composition the more satisfactory it is likely to be. Neither is it a question of producing only those waves to which our eyes are most sensitive. In that case a source emitting only yellow light would give excellent illumination, but it would be at the expense of destroying colour contrast, reducing all tints to gradations between yellow and black. Hence, a successful artificial light, if it is to render colour values correctly, must not only be rich in yellow rays, but also contain the other components of the visible spectrum in similar proportions to sunlight.

Any solid body raised to a high temperature emits light, and the easiest way is to make use of the chemical energy due to combustion. Then the cost depends more upon the price of the combustible used than upon the "efficiency" of the conversion of energy into light. An oil lamp or candle expends energy at a much greater rate for the production of a certain intensity of light than an incandescent lamp, yet it is less expensive. This is because the conversion in the former case is fairly direct. A ton of coal burned as a bonfire would give much more actual light than if burned under a boiler and its energy transformed into light through the intermediate stages of heat, mechanical motion, and electric current. So much is lost as unavailable heat in these processes that only the merest fraction becomes useful as light; what is really gained is the greater convenience of its application.

When chemical action takes place the laws of radiation are complicated by other considerations, but in electric lighting we are largely concerned with solid bodies intensely heated by the passage of an electric current, and the problem which immediately rises before us is to consider what kind of substance should be used, what shape should be given to it, and what temperature it should be raised to, in order that it may emit the most useful mixture of light waves.

After allowing for all the sources of waste before the primary energy of coal is available in the form of electrical energy for heating the substance, some mental effort is necessary to realise adequately what an enormous percentage of the portion actually expended on it is wasted in absolutely useless, because invisible, radiation The difficulty is a fundamental one, inherent in the laws of radiation themselves, and not to be overcome by any ordinary device, unless other than merely temperature effects are concerned. At any given temperature of a hot body, one particular wave length is emitted in the greatest abundance, smaller amounts of longer and shorter waves being also radiated, and although the exact value of this wave length varies slightly with the nature of the emitting substance, it corresponds to the invisible long waves of dark heat at all temperatures reached at present by incandescent lamps. Again, at any given temperature all solid bodies do not emit the same total quantity of radiation. They differ considerably in "emissivity," black bodies of the lamp-black or carbon type being the best radiators, and bright, metallic bodies the worst. We therefore select these as examples of the laws of radiation, for any other substance would probably be intermediate in its behaviour, and we give in Figure 211 curves showing the relation between radiation and wave length at temperatures of 1000° C. and 2150° C., firstly, for a "perfectly" black body (B), and secondly, for platinum (P).

To realise the meaning of these temperatures we must recollect that 1000° C. is approaching a white heat, platinum itself melts at about 1750° C., and 2150° is far beyond the range of a furnace. Hence the curve given for platinum at 2150° C. would apply to the molten state at a temperature considerably above that of fusion. This particular curve has been obtained by calculation for the sake of comparison, the

other three being taken from experimental results published by Lummer and Pringsheim.

All those wave lengths which excite the sensation of vision

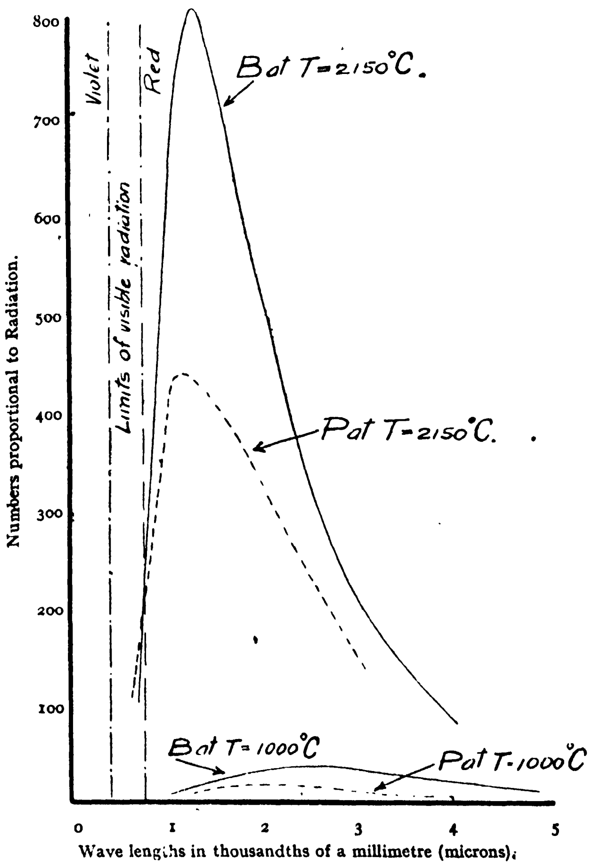


FIG. 211.

lie roughly between 0·4 and 0·75 on this scale for the extreme visible violet and red respectively, and these limits are indicated in the diagram by two vertical dotted lines. From these

curves we see (1) the total radiation at a given temperature is greater for a black body than for a bright metal. (2) Even at the high temperature of 2150° C. the great bulk of the radiation is in the form of invisible heat waves, only the merest fringe falling within the bounds of the visible spectrum. (3) An increase of temperature has two effects: it vastly increases the total radiation, and it also reduces the wave length for which that radiation is greatest, thus displacing the curve towards the useful or visible wave lengths. (4) For a given temperature the maximum radiation corresponds to a shorter wave length for platinum than for the black body, and hence, although the total radiation is much less, the curve is moved in the right direction, and the useful radiation may be a larger percentage of the whole.

Applying these facts to the present problem, we see that the ideal solution would be to run the lamp at a temperature which would bring the peak of the radiation curve somewhere near the middle of the visible wave lengths. From the nature of the case this implies a working temperature not very dissimilar to that of the sun itself. But although this ideal limit is unreachable, and although every increase of temperature increases also the radiation of useless energy, yet it increases the amount of useful radiation in a much greater degree. Lummer and others have shown that whereas the total radiation from a hot body of the carbon type increases with the fourth power of the absolute temperature, the luminous part increases at something like the twelfth power, and hence there is a really enormous relative gain in light to be obtained by even a slight rise of working temperature. Dr. Henderson states (in a paper read before the Glasgow University Physical Society) that a rise of temperature from 1800° to 1875° is sufficient to double the energy radiated as yellow light, whilst on account of the fact that the temperature of the carbon tip in an arc is about 4000° C. and that of an incandescent carbon filament about 2000° C., the former emits something like 4000 times as much luminous energy per unit of area of radiating surface as the latter.

From the same paper we take the following table of temperatures reached in various sources of light. The numbers given are of course approximate, but are probably correct within about 4 or 5 per cent.

Source of light.	Temperature in Centigrade degrees.
Arc	3700
Nernst lamp	2050
Incandescent gas	2050
Carbon filament	1700
Candle	1580

These considerations show that the ideal substance to be used in making lamp filaments must, above all things, stand the highest possible temperature without fusion or too rapid deterioration. This is the imperative condition ; if also it has naturally a high resistivity and a small positive temperature coefficient its value is enormously enhanced, and if at high temperatures it radiates more like a metal than like a black body so much the better. Such a desirable combination of qualities has yet to be found in any one substance, and as regards the last, it is necessary to be very cautious in drawing conclusions as to the radiating properties of a body at a white heat from the appearance and colour of its surface when cold.

It is, however, evident that extremely high radiating power is not necessarily a desirable property in a material to be used for lamp filaments. For if a given number of watts be supplied to the lamp the temperature rises until the loss of energy in various ways exactly balances the energy supplied to it in the same time.

LAMPS

In a good lamp the loss of energy is mainly in the form of radiation, and hence the greater the radiating power of the filament the lower will be its equilibrium temperature, and it is this which determines the ratio of useful light to invisible heat.

A bad radiator would, for the same watts, reach a higher equilibrium temperature before it could radiate the same amount of energy, and the actual light effect would be greatly increased.

The form to be given to the substance is determined by the fact that it should have the greatest possible amount of surface as compared with its volume, for only the outside counts as a source of light. Obviously we are led to the idea of an extremely thin filament of small mass as exemplified in

the ordinary incandescent lamp, and this construction is still more imperatively demanded by the conditions of economical supply. For when we say that a small lamp, for instance, takes 60 watts, we merely mean that a certain rate of consumption of energy is involved, and nothing is implied as to the form in which it is supplied. Roughly speaking, we may get something like the required light with 2 amperes at 30 volts, by using a rather short thick filament of 15 ohms resistance when hot; or with 0·6 ampere at 100 volts, which means a thinner and longer filament having 166·6 ohms resistance; or with 0·3 ampere at 200 volts, using a filament of 667 ohms resistance, which, if of the same section, must be four times as long as in the previous case (in practice, however, it would be made of smaller diameter). It will be noticed that if the voltage is doubled the resistance must be increased four times. If in other respects the lamps are equally cheap and good (which is not true), it is a matter of indifference to the consumer as to whether he uses 100-volt or 200-volt lamps, but to the supply company it is a matter of vital importance, and to them the best lamps are those which require the least current. The matter is discussed elsewhere (see p. 315), and here it is sufficient to allude to it as a factor in design which makes high resistivity in the material a most valuable property, especially for high voltage lamps of low output.

CARBON FILAMENT LAMPS

Though this type of lamp has now become practically obsolete, the method of construction and certain characteristics are still of interest. The filament is made by dissolving cellulose in a solution of zinc chloride and squirting the resulting gummy fluid through dies into alcohol which results in the production of a uniform gelatinous-looking thread. This filament is washed, dried, and, after being arranged on formers of suitable shape, carbonised by heating out of contact with air. The filaments are then treated by exposing them to the vapour of some hydrocarbon under reduced pressure whilst heated to a high temperature by the passage of a current. One function of this process is to equalise the area of cross-section of the filament in different parts, since the thin parts will get hotter and receive a more copious deposit of carbon from the decomposing gas. The process

also hardens the surface of the filament and assists in the production of batches of filaments having equal resistances, which is necessary if the different filaments are to give equal values of light output when the same value of voltage is applied to each. When, after various further processes, the filament is enclosed in the lamp bulb, with metal connections sealed into the glass, the latter must be exhausted to an extremely high degree and, during this operation, the filament and bulb must be heated to a temperature as high as, or higher than, they are likely to attain afterwards, in order to expel various gases mechanically absorbed by both filament and glass. This exhaustion is not merely to prevent combustion (since the presence of any inert gas would serve for that purpose, or even a moderately good vacuum), but is also required to prevent undue cooling of the filament by convection.

Carbon filament lamps, largely owing to the negative temperature coefficient of resistance of carbon, give an output which is very considerably affected by change of applied voltage, an increase of voltage of 4 per cent resulting in an increase of output by approximately 24 per cent, but with a reduction in useful life (which is commonly terminated by reduction of output by internal blackening of the bulb due to vaporised carbon) of 40 per cent to 50 per cent.

The efficiency of a carbon lamp is low, but is obviously dependent on the useful life for which the lamp is designed, the nature of the relationship being indicated in the following table. For the meaning of the term " lumen " see page 337.

Efficiency (lumens per watt)	6·3	5·0	4·2	3·6	3·15	2·8
Life in hours until initial output has fallen 20 per cent	40	190	500	900	2600	5000

In practice it has been necessary to make a compromise between long useful life on the one hand and lower efficiency on the other, and it has been usual to run lamps at such an efficiency as to give a useful life of something like 800 hours.

USE OF METALLIC FILAMENTS IN LAMPS

The advent of the metallic filament has been due to the search for a material capable of working at a higher temperature than is possible when carbon is used. As a matter of

fact, platinum was tried for filaments in the earliest days of the glow lamp, before the time of carbon, but it was a failure chiefly because its fusing point was too low, and the success of the carbon lamp diverted attention from metals for many years. More recently the metals osmium, tantalum, and tungsten have been used for filaments, and of these tungsten has proved to be the most successful on account of its high melting-point (say 3300° C.), allowing of the use of a high working temperature, and of its great mechanical strength which is much higher than that of steel. The resistivity of tungsten is much lower than the corresponding value for carbon and this necessitates the use of long filaments of small diameter. Tungsten has a positive temperature coefficient of resistance, and this, while making the tungsten lamp less sensitive than the carbon lamp to variations of voltage, also causes the resistance of the filament when cold to be much lower than the resistance at a working temperature, and large-powered lamps may take a considerable momentary current when first switched on to a circuit.

For a considerable time difficulty was experienced in making long lengths of tungsten filament, and many different processes were tried, but it is now possible to manufacture drawn tungsten wires of small diameter in long lengths, thus making feasible the almost universal use of this material for lamp filaments.

The following information concerning the modern method of production of tungsten wire is extracted from a paper by Mr. F. J. Hawkins, A.M.I.E.E., and has been placed at the disposal of the writer by the British Thomson-Houston Co., well known as the makers of Mazda lamps. The most common ores containing tungsten are wolframite, hübnerite, and scheelite, and the ore is first crushed and screened to secure material of suitable fineness. After roasting the ore is treated with boiling hydrochloric acid, to which a small percentage of nitric acid has been added, and in due course crude tungstic acid is thrown down as a precipitate while various impurities remain in solution. The tungstic acid is dissolved in ammonia solution and, by crystallization, ammonium tungstate is obtained, this material being next decomposed by acid to obtain a purer tungstic acid, the whole cycle of purification operations being repeated several times. The tungstic acid

is finally dried and reduced in a stream of hydrogen at a temperature of about 1000° C., the resulting product being metallic tungsten in the form of a dark grey powder. This powder is hydraulically pressed in steel moulds and formed into square bars of ¼ inch side and about 16 inches long, which are then heated to make the particles more adherent. The bar is next "sintered" by raising it to a temperature of 3000° C. in a stream of hydrogen, and this process removes impurities and causes the crystals to adhere more firmly to each other though the bar still remains very brittle. The bar is then subjected to a hammering process known as "swaging" to give it a more fibrous structure, and finally formed into wire of the required diameter by drawing through diamond dies, graphite being used as a lubricant.

METALLIC FILAMENT LAMPS OF THE VACUUM TYPE

Early metallic filament lamps were invariably of the vacuum type, the reasons leading to the use of this arrangement being the same as in the case of the carbon filament lamp. Since there are no cooling effects due to convection to be feared with the high vacuo employed, the filament was arranged in a very open manner which is the best type of construction from the point of view of light radiating properties. Recently, however, filaments in the form of a closely wound helix, as used in gas-filled lamps, have been employed. Vacuum type lamps are still used for small outputs, but there is a constant tendency for the gas-filled type to encroach on what has been regarded as the sphere of the vacuum type of lamp.

METALLIC FILAMENT LAMPS OF THE GAS-FILLED TYPE

It has been stated in the early part of this chapter that the higher the temperature of a solid radiating body, the greater is the total radiation per unit area of surface of the body and the greater the proportion (at any rate up to far higher temperatures than are at present attainable) of the total radiation which is useful for lighting purposes. In the vacuum type of lamp, having a tungsten filament, the working temperature is of the order of 2050° C., and this is far below the melting-point of tungsten, which is near 3300° C. It

would appear at first sight, therefore, that there is ample margin with tungsten filaments for the use of higher temperatures. The real limitation of temperature of filament in the vacuum lamp is, however, evaporation of the material of the filament which, in addition to reducing the life of the filament directly, also causes an internal blackening of the bulb owing to the condensation thereon of the vaporised tungsten. It is a matter of common knowledge that such a substance as water vaporises more readily under low than under high air pressures, and the same state of affairs applies to the direct vaporisation of a solid such as tungsten or carbon. The high vacuum in the older type of tungsten lamp is, therefore, very favourable to ease of evaporation of the metal which, however, can be minimised by surrounding the filament with an inert gas. Using such a gas in the bulb permits of the use of higher filament temperatures for a given rate of evaporation of the filament and this, in itself, will lead to higher lamp efficiencies.

Unfortunately, however, the presence of the inert gas causes a considerable loss of power from the filament by convection, and the question arises as to whether the gain in efficiency due to the higher working temperature is likely to be more or less important than the loss in efficiency due to convection.[1]

If we consider a series of wires of various diameters but all running at the same temperature, it would appear that both the rate of emission of light and the power lost by convection would be proportional to the area of surface of the wire concerned, and, in wires of comparatively large diameter, experience shows this to be nearly true. With smaller wires, however, experience shows that the loss by convection does not diminish in proportion with the area of surface but at some smaller rate. This is due to the fact that the hot wire is surrounded by a quiescent layer of hot gas, and convection takes place from the outer surface of this layer rather than from the actual surface of the wire. The thickness of this layer of gas does not depend materially on the diameter of the

[1] For much of the information given in connection with gas-filled lamps, and in connection with lamps having Pearl bulbs, the writer is indebted to the General Electric Co., Ltd. (who are concerned with the manufacture of Osram lamps), who have permitted him to use the information in the excellent pamphlets issued by their Research Laboratories.

wire, and in the case of wires of large diameter the effective increase in diameter (from the point of view of cooling) is very small proportionally, but in the case of wires of small diameter the effective increase in diameter is very large proportionally, and thus for small wires the ratio $\frac{\text{power emitted in form of light}}{\text{power lost due to convection}}$ decreases and results in a serious loss of efficiency.

In practice it is found that for filaments of the diameters usually required in lamps, the loss due to convection more than wipes out, so far as efficiency is concerned, the gain due to the higher filament temperature. With filaments of larger diameter, however, the effect of convection is proportionally less important and the use of a gas filling may result, on the whole, in a higher lamp efficiency.

Now in lamps of ordinary wattage it is possible to use thin filaments only, since the area of emitting surface is fixed by the light output required, and the resistance is fixed by the input current and voltage. If, however, the filament is wound in the form of a close helix, we can, while retaining the necessary resistance, get a radiating body whose radiation and convection depend upon the area of surface of the cylinder formed by the helix rather than upon the area of surface of the filament itself. In other words, we have a radiating body of such large diameter that the increase in radiating area due to the gas film becomes comparatively unimportant and does not wipe out the gain in efficiency due to the higher temperature made possible by the surrounding gas.

The effect is illustrated in Figure 212, which shows wires

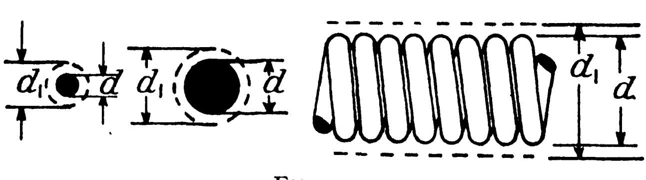


FIG. 212.

of small and large diameter and also a closely wound helix composed of wire of small diameter. In each case d is the effective diameter from the point of view of radiation, while

d_1 is the effective diameter from the point of view of convection. The distance between the continuous and dotted lines represents the approximately constant thickness of the layer of hot quiescent gas. The gas used in the bulb should of course be inert and of a heavy nature so as to give a low inherent convection loss ; argon, or argon mixed with a little nitrogen, is commonly used.

LAMPS WITH PEARL FINISHED BULBS

With the increased filament temperatures which have become usual in electric lamps during recent years, there has been an increase in intrinsic brilliancy of the filament

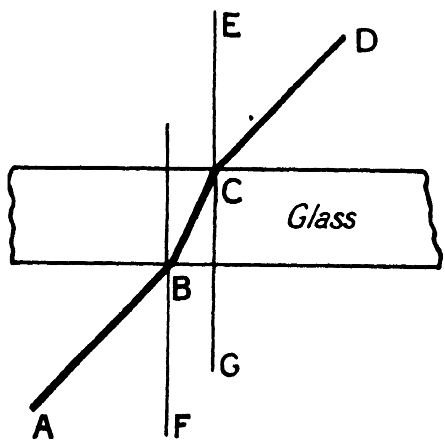


FIG. 213.

(measured in candle power or lumens per unit area) and this has resulted in trouble due to glare when the filament is viewed directly. To overcome this defect several devices have been tried such as external frosting, external spraying, and the use of opal glass. Unfortunately, all these methods result in a serious diminution of light emission, and, in the case of frosted and sprayed lamps, the amount of light absorbed by the diffusing device increases with the age of the lamps owing to the collection of dirt on the roughened surface.

It has been found, however, that if the bulb is frosted internally, not only is there no possibility of the collection of dirt on the roughened surface, but, while still securing adequate diffusion of the light, the loss by absorption is much reduced. This is due to a well-recognised optical phenomenon known as total internal reflection.

When a beam of light passes obliquely through a plane sheet of glass it is bent on entry and again on exit, the emerging ray CD (see Figure 213) being parallel to the entering

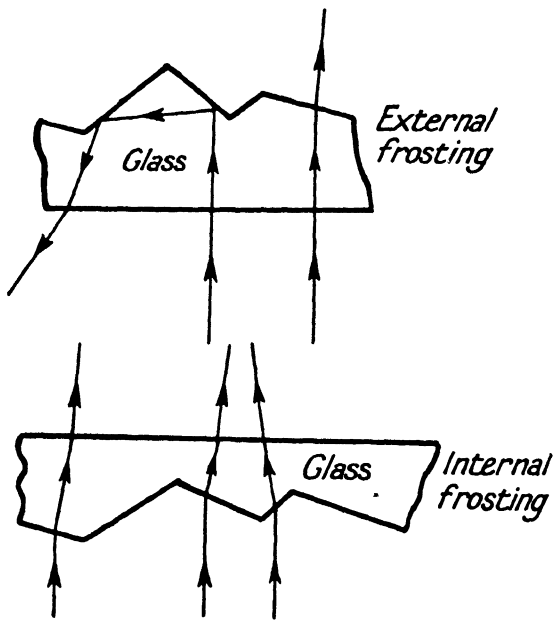


FIG. 214.

ray AB. When this ray reaches the first surface of the glass, most of the light enters the glass, very little being reflected unless the angle ABF approaches a right angle. The state of affairs is very different when the ray reaches the second surface of the glass, and, in this case, if the angle of incidence BCG

is greater than 41° no light passes into the air, the whole of it being reflected internally.

Now the frosted surface of a glass bulb may be looked on as being composed of a very large number of little facets lying at various angles to the general surface of the glass, and, if the frosting is on the outside of the bulb, a proportion of the rays passing radially outwards from the filament are likely to meet the facets on the outer surface of the glass at such an angle as will lead to total internal reflection. Of course a part of such reflected rays will ultimately get out of the glass at other points, perhaps after further reflections, but the passage through an increased thickness of glass will certainly cause increased absorption of light.

If, however, the irregularly disposed facets due to frosting are on the inside of the glass, the majority of the rays will secure entry to the glass whatever the angle of incidence, and, owing to the even external surface of the glass, few rays are likely to meet with total internal reflection at that point. The phenomenon is illustrated in Figure 214, which is based on a diagram supplied by the General Electric Co. The effect is very marked as may be gathered from an examination of the table given below which shows the additional light absorption (over and above that due to a clear glass bulb, which may be taken at 1·5 per cent) caused by various methods of diffusion.

Type of bulb.	Percentage of light absorbed by the diffusing medium.
Opal glass	8 per cent and upwards
White sprayed*	6 to 8 per cent
Externally frosted	4½ to 5½ per cent
Internally frosted	1 to 2 per cent

MODERN METHODS OF MANUFACTURE OF METALLIC FILAMENT LAMPS

For the following particulars the writer is indebted to the paper entitled *Manufacture of Electric Lamps*, by Mr. F. T. Hawkins, A.M.I.E.E., which has been previously mentioned, and they refer to the methods use in the manufacture of Mazda lamps.

The most remarkable change which has taken place in recent years in connection with lamp manufacture has been

the introduction of automatic machines to such an extent as to almost exclude hand operations. Glass bulbs having a diameter less than 10 cms. are usually blown by machines from Soda Lime glass; the machines are of large size, carrying in their tanks as much as 40 tons of molten glass, and they are provided with a number of heads, thus allowing for the production of as many as 24 bulbs (in various stages of progress) taking place simultaneously. The total output of such a machine may be so high as 55,000 bulbs in 24 hours. After blowing, the bulbs are annealed in order to release any strains produced in the previous operations and leave the annealing oven at a temperature of from 300° C. to 350° C. The glass rods and tubes necessary for the lamps are also produced in automatic machines, and the products obtained are much more uniform than was possible with hand drawing and include a much smaller proportion of outsize material. The brass for the caps is stamped to size and brought to the desired shape by pressing operations; the pins are inserted in caps of the B.C. type and the threads rolled in caps of the screw type prior to the process of vitriting. The lead-in wire consists of three parts, electrically impulse-welded together; the portion running from the contacts to the glass is of copper, the part sealed through the glass is of platinum or a suitable substitute (a material having a thermal coefficient of linear expansion similar to that of glass and which permits of the formation of an air-tight seal being necessary), while the portion inside the bulb is of constantan or copper.

The stem, which is also assembled in rotary automatic machines, comprises a length of stem tube (one end of which is flared for ultimate sealing to the bulb, the other end being used for the formation of the pinch through which the leading in wires are sealed) from which a length of glass rod, to carry the filament supports, projects at one end while a thin glass tube, for use in exhausting the bulb (and also for the admission of gas in gas-filled lamps), projects at the other end. Both rod and thin tube are sealed to the stem tube and, by means of compressed air, a small aperture is made from the exhausting tube through the wall of the stem tube thus giving access, at a later stage of the operations, to the interior of the bulb. A careful examination of a modern type of bulb will show clearly the arrangement indicated. The filament

supports are of tungsten or molybdenum and are inserted into hubs formed on the glass rod, the whole process being again carried out in automatic machines. At present the actual mounting of the filament is usually performed by hand, and is one of the few operations in modern lamp manufacture performed in this way; great care is necessary, particularly with filaments for gas-filled lamps, in order to prevent damage or distortion of the filament. The filament wire is secured to the leading in wires by clamping or by electrical spot welding. The next process is to insert the mounted filament into the bulb, which has previously been carefully cleaned, and seal the flare of the stem to the bulb. These operations are carried out in machines, but hand-made adjustments are usually necessary.

Exhaustion of the bulb is also carried out in machines, a rough pump being used to extract the greater part of the air while the finishing pump is of the rotary oil-immersed type. The lamps are heated to 350° C. approximately during the process, and, in the case of gas-filled lamps, the inert gas is admitted at the correct pressure after exhaustion and immediately prior to sealing off. Even after exhausting in the manner described, trouble may still be experienced due to residual gas derived from the glass, filament, metal supports, and leads, which is freed when these parts become heated, and, to obviate risk of flashing over inside the lamp due to this cause, a small amount of phosphorus (or other suitable material) is inserted into the bulb in the course of manufacture and the lamp run on an over-voltage for a short time. The parts in which residual gas is secreted thus become hotter than in normal operation and the gas is driven out and readily combines with the phosphorus which has been vaporised by heat from the filament. The lamps are finally capped, cleaned, and the bulb sprayed or etched externally if required, any irregularities in the filament being readily detected by running the lamp (prior to obscuring) on about half voltage.

EFFECT OF CHANGE OF VOLTAGE ON METALLIC FILAMENT LAMPS

The output and life of a filament of specified size is largely affected by small changes of applied voltage; thus, it is stated by the Research Laboratories of the General Electric Co., in

the case of filaments situated in a vacuum an increase of voltage of 1 per cent increases the output by 4 per cent, increases the efficiency by 2·4 per cent, and decreases the life by 16 per cent., the corresponding figures in the case of a large gas-filled lamp being 3·6 per cent, 2·1 and 12 per cent respectively.

RATING AND EFFICIENCY OF METALLIC FILAMENT LAMPS

The input of a filament lamp can obviously be expressed very conveniently in watts, but the output is not so readily specified. In the past, it has been usual to express output in terms of the Candle Power, which was originally the luminous intensity given by a candle of specified construction burning under suitable conditions. The candle, as a practical standard, has long since been superseded by other devices of a more convenient nature. The chief practical objection to stating the output of a lamp in terms of the Candle Power (C.P.) is due to the fact that every lamp gives different intensities in different directions, and thus the C.P. of a lamp apparently varies with the position of the observer. This point is illustrated in Figures 218 and 225. One way of overcoming this difficulty is to make use of the mean spherical candle power of a lamp which is the average C.P., taking every direction of emission of light into due account.[1]

It is now, however, becoming usual to express the rate of light emission from a lamp (i.e. the luminous flux from a lamp) in terms of the lumen. If a lamp gives an intensity of one C.P. in all directions its rate of light emission (or luminous flux) is said to be 4π lumens, or one lumen per unit solid angle. If we express the output in terms of the lumen, the statement is quite independent of the distribution of intensity from the lamp in different directions.

Again, in the past, the efficiency of a filament lamp has been expressed by stating the watts per C.P. This method, apart from the difficulty in regard to the C.P. which has been mentioned already, is bad because it gives the ratio of input to

[1] Occasionally the expressions "mean hemispherical candle power" and "mean horizontal candle power" are met with. The former indicates the average C.P. in all directions below the plane passing through the centre of the lamp, while the latter is used to indicate the average C.P. in all directions in the horizontal plane passing through the centre of the lamp.

output which is a measure of inefficiency rather than of efficiency, It is now customary to express the efficiency in lumens per watt, which has the twofold merit of being a real expression of efficiency and of having a perfectly definite meaning.

The size of a metallic filament lamp is expressed by stating its input in watts, and the standard sizes include, amongst others, those taking 25, 40, 60, 100, 150, 300, 500, and 1000 watts. The table given below gives information concerning the output and efficiency of typical examples of filament lamps for voltages of about 230.

Type of lamp.	Input (watts).	Output (lumens).	Efficiency (lumens per watt).	Watts per C.P. (approximate).
Carbon filament (32 C.P. nominal)	120	350	2·92	4·3
Metal filament (Vacuum type)	40	348	8·7	1·45
Metal filament (Gas-filled)	60	594	9·9	1·27
Metal filament (Gas-filled)	100	1160	11·6	1·08
Metal filament (Gas-filled)	500	7500	15·0	0·84

COSTS OF OPERATION OF FILAMENT LAMPS

The cost of operating a filament lamp can be divided into two parts, (*a*) the cost of energy, and (*b*) the cost of renewals. The most economical lamp to employ will be the one for which the sum of these two parts of the total cost comes out to be lowest. Since lamps having wide variations of rating may be under consideration it is necessary to reduce the costs to a common basis of light output, a convenient unit for this purpose being 10,000 lumen-hours. The table given below contains the results of such a comparison, energy being charged at the rate of threepence per B.O.T. unit.

					Cost per 10,000 lumen-hours (pence).		
Type of lamp.	Input (watts).	Output (lumens).	Initial cost (pence).	Life (hours).	Energy.	Renewals.	Total.
Carbon filament.	120	350	21	800	10·28	0·75	11·03
Metal filament (Vacuum)	40	348	26	1500	3·45	0·50	3·95
Metal filament (Gas-filled)	100	1160	41	1000	2·58	0·35	2·93
Metal filament (Gas-filled)	500	7500	162	1000	2·00	0·22	2·22

Taking the case of the carbon lamp as an example the costs are obtained as follows :—

Energy Cost —If the lamp is burned for one hour 350 lumen-hours of light output will be obtained. The energy consumed will be 0·12 B.O.T. unit and will cost 0·36 penny. By proportion it will be seen that 10,000 lumen-hours will cost $\frac{10,000 \times 0{\cdot}36}{350} = 10{\cdot}28$ pence.

Renewal Cost.—If the lamp is burned until its life is ended, any falling off in output being neglected, 350×800 lumen-hours will be obtained, and the cost will be 21 pence. By proportion the renewal cost per 10,000 lumen-hours will be $\frac{10,000 \times 21}{350 \times 800} = 0{\cdot}75$ penny.

ARC LAMPS

The P.D. required to produce a spark, say, one inch long, between two conductors in air at ordinary pressures is something like 50,000 volts, and hence they may be brought very close together at moderate voltages without any effect whatever. If, however, they are allowed to touch and are then slightly separated, or if a momentary spark be produced by some higher voltage, the current tends to persist across the gap forming what is known as an arc, and the ends of the conductors become intensely heated.

For lighting purposes, the conductors are usually made of carbon, and in the older types of arc lamps we may regard the formation of an arc as merely a new method of raising two carbon tips to an extremely high temperature, much higher, in fact, than can be obtained in any other way; thereby making them very efficient sources of light. It is still a temperature radiation, and as before the efficiency is limited by the fact that most of the energy, about 90 per cent, is radiated as invisible heat.

The formation of a true arc depends chiefly upon the nature of the negative electrode. From the material of this electrode is derived the stream of conducting or "ionised" particles which constitutes the current in the gap, and if it is unable to supply such a stream readily, it is difficult to maintain an arc at all. Hence the negative electrode *must* be hot, whereas it does not matter whether the positive electrode is hot or not,

and, within certain limits, it does not matter much what it is made of. But during use, the positive electrode *does* actually become the hotter, unless some measures are taken to prevent it, and is therefore, in the old D.C. carbon arc, the most important source of light.

Direct current arcs may readily be formed between metallic conductors of high melting point, such as iron, but with less readiness with metals of lower fusing point, such as zinc. When alternating current is used, each electrode has to supply conducting particles in turn, as it becomes negative. In fact the arc dies out at each reversal, and has to be restarted in the opposite direction before the bridge of ions ceases to conduct. This is possible with carbon electrodes, but it is always difficult, and as a rule almost impossible, to run metallic arcs with A.C. It is not surprising, therefore, to find that A.C. arcs are less efficient and satisfactory than D.C. arcs. In the past arc lamps have been of great importance in general illumination practice, but in recent years they have been largely superseded by high-power gas-filled filament lamps which require far less attention. As, however, they have certain important special uses in connection with photographic and projection work, it is necessary to pay some attention to the physical aspect of the arc and to outline the principles of arc lamp mechanism.

For convenience we may group arcs into three types :—

(1) Open arcs.
(2) Enclosed arcs.
(3) Flame or luminous arcs.

Each of these types may be operated by either direct or alternating current.

DIRECT CURRENT OPEN ARC LAMPS

In an "open" arc the carbons are freely exposed to the surrounding air, and the enclosing globes are only used for mechanical protection or to diffuse the light. It is the oldest form of arc, and, as a rule, the distance between the carbon tips is quite small, $\frac{1}{8}$ to $\frac{3}{16}$ inch, and a P.D. of at least 40 volts is required between them to ensure steady working. With ordinary carbons the current will then be from 8 to 15 amperes.

It should be noticed that it is not possible to run a smaller

arc with a smaller P.D. Below the minimum voltage a true arc cannot be maintained. This minimum depends upon the nature of the arc to some extent; for instance, it is about 33 volts with alternating currents.

If the voltage be increased the arc can be made longer, but as the light practically all comes from the carbons, there is a distinct loss of efficiency in expending energy to maintain a long and but slightly luminous arc, unless there is some other advantage to be obtained.

It must be pointed out that we are dealing with a part of the circuit which does not follow the ordinary form of Ohm's Law. This is partly because an increase of current enlarges the luminous area, and as the area of section of the gaseous conductor is thereby increased the equivalent resistance falls. The relation between current and P.D. is very complicated, and it is quite usual to find an increase of current corresponding to a decrease in P.D. between carbons and vice versa. We do not propose to discuss the theory of the arc itself here, although we may remark that its general behaviour is much the same as if it were the seat of a back E.M.F. of about 39 volts (for a direct-current open arc). Opinion is divided as to the reality of this back E.M.F., and personally we believe the facts are susceptible of another explanation. The important point at present is the deduction that a ballast resistance in series will be absolutely essential to steady working.

The arc itself is not a uniform flow, but is a highly complex non-symmetrical discharge, and a study of its behaviour would lead us aside into questions as to the nature of electric discharges in general. The obvious facts are that the positive carbon gives out most of the light and wastes away most quickly, a small hollow or "crater" forming on the end of it, from which the discharge starts and which constitutes the effective luminous portion; whilst the negative carbon becomes pointed and gives out much less light. This is shown in Figure 216A. The waste is mainly due to oxidisation by atmospheric oxygen, and the difference in light-giving power is probably the natural consequence of a difference in temperature, that of the positive crater being from 3500 to 4000° C., whereas the negative tip is at least 1000° lower.

The most important light source is therefore the positive crater, the small amount of bluish light given out by the arc

itself being negligible in comparison. Hence with a given current there is apparently no advantage in increasing the arc length beyond the necessary minimum, for the extra energy represented by the increased voltage is mainly expended in the column of gas; but in reality there is a distinct gain, due to the fact that more of the positive crater is now visible. For one of the greatest disadvantages of the open arc is the screening of the light source by the negative carbon, and much work has been done to get over this difficulty.

The light-giving power (per unit area) of the crater itself is very remarkably constant, as an increase in current strength merely enlarges the luminous area without making it brighter. Its value is probably not far from 150 C.P. per square millimetre of surface (although some investigators have found a much smaller value).

To compensate for unequal consumption of carbons, the positive is usually made about twice the section of the negative, and for a long time "cored" carbons have been in use, i.e. carbons with a small central core of a softer composition containing metallic salts. These salts volatilise and pour into the gap a better conducting vapour, and as a result the arc tends to keep its central position instead of wandering over the surface of the carbon. It is usual to make the positive carbon the upper one, because then the light is distributed where it is wanted, practically none being lost by upward radiation. This is of great importance in outdoor work.

As might be expected from the high temperatures reached, the efficiency is very good. After allowing for losses in the lamp windings, etc., it is from 18 to 25 lumens per watt for direct current arcs. This may of course be largely reduced by the use of opalescent globes, although they improve the general effect. For instance, an ordinary 10-amp. 50-volt open arc may give about 1000 c.p. (mean hemispherical) without a globe, and with a globe this may be reduced by anything up to 30 or 40 per cent, according to the opacity (or dirtiness) of the globe.

To ensure steady running at constant voltage a ballast resistance must be put in series with the arc, for evidently the latter has no true resistance, and therefore violent fluctuations of current may occur. Such a resistance is best regarded as a contrivance which automatically varies the voltage on the

arc itself. For suppose the voltage on the lamp is kept constant at 50, and that the resistance of the lamp itself is 0·5 ohm when the carbons are in contact, it is obvious that the current may be as much as 100 amperes at starting, or if the carbons do not feed properly. If, however, a 1-ohm resistance be put in series with the lamp, the maximum current with carbons in contact will be $\frac{50}{1\cdot5}=33\frac{1}{3}$ amperes. But we may consider that with the working current of 10 amperes the steadying resistance uses $10\times1=10$ volts, leaving 40 volts available for the lamp. If, however, the current for some reason rises to 20 amperes, the resistance takes 20 volts, and the voltage on lamp is reduced to 30, it cannot work properly and current diminishes. Hence, as the arc varies in length and apparent resistance, the volts on it rise and fall in a way that tends to keep the current constant, although the voltage on the lamp as a whole is invariable.

Modern lighting circuits have usually a voltage of about 230, and a single open arc lamp cannot be run economically on such circuits with direct currents. An enclosed arc may then be used with advantage (see p. 345).

It is possible, however, to run four or five lamps in series on 230 volts, in which case they will tend to steady each other and reduce the amount of ballast required. Some contrivance is then necessary to prevent an accident to one lamp throwing the others out of action.

Such a device is shown in Figure 215, from which it will be seen that should the series circuit fail in a particular lamp, the excess voltage across the lamp will strongly energise the shunt coil C of the cut-out with the result that the contact K will be closed, thus shunting the defective lamp by the resistance shown in the Figure, the contact K being kept closed by the combined effects of the series and shunt coils on the magnet of the cut-out.

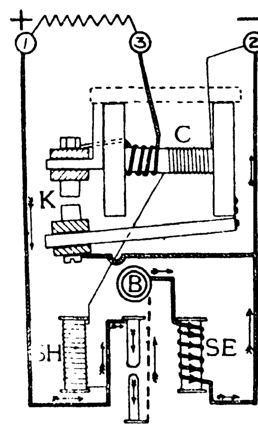


FIG. 215.

It is essential that the defective lamp be shunted by a

resistance rather than completely short-circuited in order that the normal voltage be maintained on the remaining lamps of the series.

For projection work the carbons in a D.C. open arc are sometimes arranged as in Figure 217, which permits of unobstructed passage of the rays from the positive crater to the condenser lens of the projection apparatus.

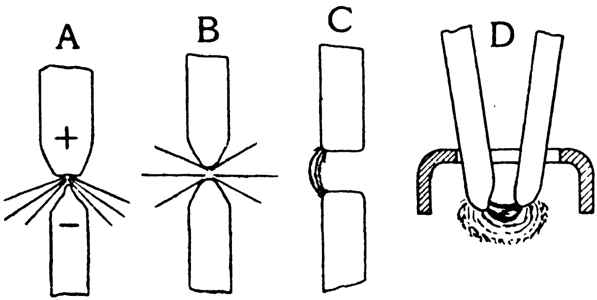


FIG. 216.

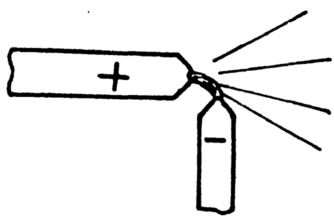


FIG. 217.

ALTERNATING CURRENT OPEN ARC LAMPS

In this case no crater forms and both carbons must behave exactly alike. Probably neither reaches the high temperature of the positive crater, and thus there is an inevitable reduction in efficiency, which may be taken at from one-half to two-thirds of that of the direct current arc. It is found, however, that such arcs can be run steadily at a rather lower voltage (the minimum being about 33 volts) than is required in the former case, and further, there is a distinct saving due to the

fact that a choking coil may be used for ballast instead of a wasteful resistance. But on the whole the alternating arc is much inferior to the direct current arc. One source of loss is due to the direction of the emitted light. This is just as much upwards as downwards, and in practice means a serious waste (see Figure 216B).

Although there is no doubt as to the fact, it cannot be said that the actual reasons for this inferiority are yet definitely determined. Some observers have found the brilliancy of the carbon tips per unit of area to be the same as that of the positive crater itself.

A single alternating arc may be used economically on a 230-volt circuit either by putting a choking coil in series with it, or by running it from a suitable transformer.

ENCLOSED ARCS

With the introduction of these lamps about 1895, commenced a very important era of development. They were called into existence by the demand for a lamp which could run singly and with little trouble on 115 or 230-volt circuits. This in itself, apart from working difficulties thereby introduced, merely means a longer arc; but by enclosing this in an almost air-tight space, so that the oxygen present is speedily used up and can only be very slowly renewed by diffusion from the surrounding atmosphere, the rapid waste due to combustion which takes place in the open arc is very greatly reduced and a lamp is obtained which will run for very long periods (from 70 to 200 hours) without attention or renewal of the carbons. Thus the distinguishing features of an enclosed arc are a semi-airtight enclosure and a much longer gap than usual between the carbons.

In addition to the above advantages there is no longer any necessity for an almost continuous and delicate feed; the carbons will only need advancing at comparatively long intervals, and a perceptible flicker in the light at that instant is of little importance, and in consequence the lamp mechanism is simplified and rendered less expensive.

As an offset to these advantages there is the serious loss of light due to deposits forming on the enclosing globe and a variation in brightness due to flickering movements of the arc

which makes an opalescent globe, and hence further loss, almost essential. Finally, there is a very marked drop in efficiency. The direct-current enclosed arc may reach about from one-half to two-thirds that of an open arc under favourable conditions, but the alternating current enclosed arc is very unsatisfactory and has frequently an efficiency no greater than that of an ordinary incandescent carbon lamp.

Enclosed arc carbons remain nearly flat at the ends, instead of becoming rounded; and the incessant movements of the arc largely prevent the characteristic crater formation even with continuous currents (see Figure 216C). The long gap is decidedly useful in allowing light to escape better, but as the bluish light given out by the arc itself is both faint and objectionable in tint, the energy expended in maintaining it is mostly wasted. It was the very great practical convenience of having a simple inexpensive lamp which could be used independently on all sorts of voltages and circuits and needed the minimum of attention, which made the enclosed arc a commercial success.

For instance, if lamps of comparatively short-burning period were used for street lighting in a town, it was necessary to attend to all of them early every morning in order to be prepared for emergencies such as a sudden fog. But if enclosed lamps of long-burning period were used the attention required could be spread over the working day, and there was no danger of being caught unprepared.

FLAME ARC LAMPS

In these the arc itself becomes the most important source of light, even more important than the carbon tips. These lamps embody the most recent developments in arc lighting, and as a rule contain two distinctly new features. First, there is the downward feed, i.e. instead of placing the carbons one above the other, so that the lower one offers the maximum obstruction to the light, they are placed side by side and slide or are fed to one another at some small angle of inclination. Thus the arc is quite unobscured from below, but as its natural tendency is to climb upwards, following the rising column of hot gases, some device must be used to keep it at the bottom. This is managed by sending the working current

through a few turns wound on a simple electro-magnet which produces a field at right angles to the arc and in the direction required to repel it downwards. Too strong a field would blow it out altogether, just as is done in magnetic blow-outs for suppressing sparking.

The second novel feature depends upon the use of special carbons. These are of much smaller diameter (high current density tends to steady the arc) than usual, and are either impregnated throughout or are merely thin shells of carbon surrounding a central core containing a mixture of various metallic salts, those of calcium being most largely represented, but which varies in composition according to the colour effect desired. These salts become volatilised and form a vapour which becomes intensely luminous, not so much probably on account of temperature as on account of the electric stimulus due to the passage of a current. In consequence of the increased conductivity of the arc, the carbons can be separated further than usual for a given voltage, thus increasing the volume of luminous vapour, and this is made much more effective by being spread out magnetically into a large radiating mass of "flame" (see Figure 216D). As the source of light is now a gas and not a solid the light is concentrated in certain wave lengths; but by using suitable mixtures of salts these wave lengths may be spread over the whole range of vision so that the result is equivalent to a white light, or they may be made especially rich in yellow or red rays to suit the peculiarities of the human eye.

The laws of radiation discussed previously for incandescent solids do not apply to a case of this sort, and the efficiency is no longer a question of temperature. A similar remark also applies to the case of the mercury lamp; it really amounts to saying that "heat" is no longer a necessary intermediate step in the conversion of electrical energy into light, but space does not enable us to discuss the matter more fully. The practical result is a remarkably high efficiency, something like 45 lumens per watt (without globe).

The increased size of the radiating area is a great advantage, for reasons already given. Again, there is little loss of light by upward radiation. The disadvantages are rapid consumption of carbons, and therefore more frequent renewal even when using carbons of considerable length, and the inevitable

formation of fumes which coat the globe and tend to injure the lamp mechanism.

A rather important part of a flame arc is the " economiser." This is a shallow cup of highly refractory material surrounding the carbon tips which just pass through two holes in it. Although apparently simple, its presence, and the exact position of the arc with respect to it, have a very great influence on the working. It tends to protect the arc from draughts, to which all long arcs are naturally susceptible ; it limits the access of oxygen, and thus reduces the waste of carbon ; it checks the upward rise of rapour, and by becoming heated itself tends to keep up the temperature and assist radiation.

The really great drawback of the simple flame arc is the very short burning period. On the average a single pair of carbons will not last more than seven to ten hours, although much longer periods are said to have been obtained. Hence either very long carbons, or else a magazine of carbons, must be used. In the former case there are two drawbacks. First, the lamp itself is very long. This is not altogether a disadvantage, for it keeps the mechanism well above the heat and fumes. Second, there is a serious voltage drop due to the increased resistance of the carbons. In some cases this is reduced by running a metal wire through the length of the carbon, which helps to convey the current to the tips and burns away with them. Another remedy is to feed in current near the tips.

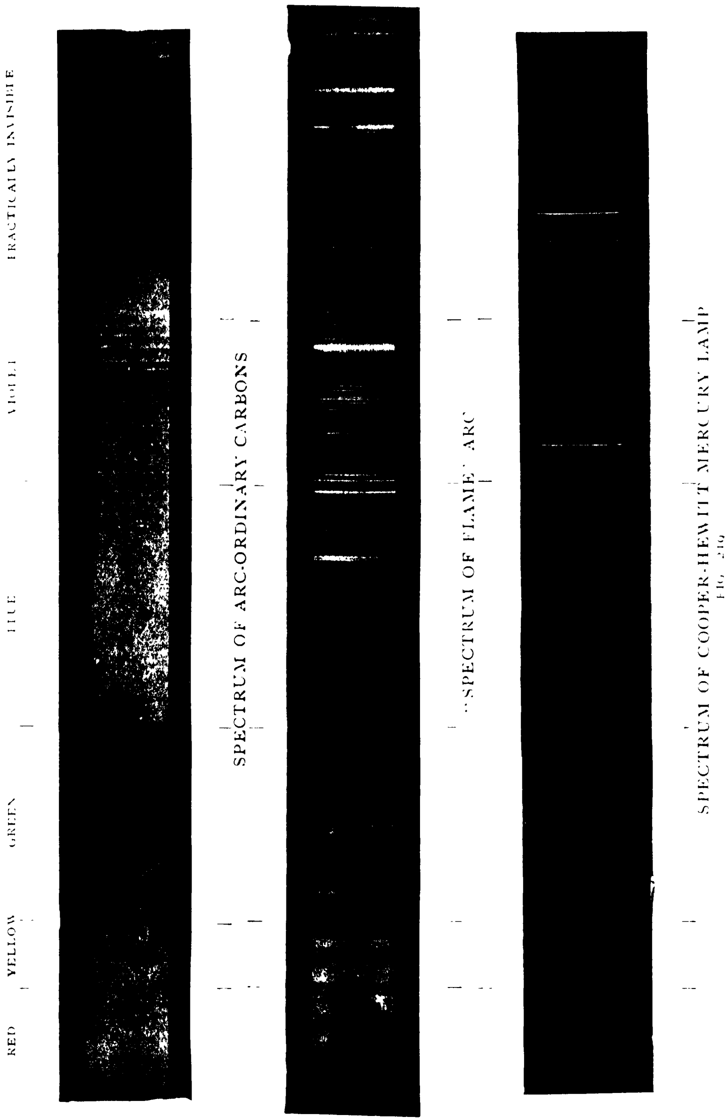
A magazine lamp, on the other hand, has the disadvantage of greatly increased complexity.

The relative outputs and the variations in intensity in different directions for the principle types of arcs are shown in Figure 218, in which A, B, and C are the polar curves for open, enclosed, and flame arcs respectively. A line drawn from the source of light O to any point on the curves gives the actual C.P. in that direction to scale, and the mean hemispherical C.P. of each lamp is indicated by a dotted line.

In Figure 219, Plate X, are shown the spectra of (1) an ordinary open arc ; (2) a flame arc ; (3) Cooper-Hewitt mercury lamp.

These were photographed successively with the same setting of the spectrograph, and are therefore strictly comparable.

It will be noticed that in the first case the light is mainly



SPECTRUM OF ARC-ORDINARY CARBONS

SPECTRUM OF FLAME ARC

SPECTRUM OF COOPER-HEWITT MERCURY LAMP

FIG. 210

To face page 348

due to the continuous spectrum of the white-hot carbons, although some lines and bands are seen in the less luminous blue and violet region and beyond. These are due to metallic impurities always present, and to cyanogen, which appears to be formed in all arcs. In the second case there are many

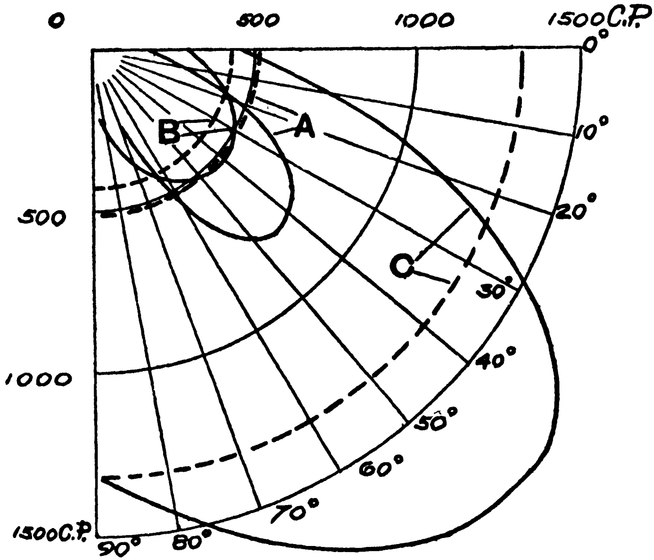


FIG. 218.

bright lines, and the radiation is especially intense in the red and yellow. The diminished effect in the green is mainly due to the plates used, which have a minimum of sensitiveness in that region.

In the third case there are only a few bright lines in which all the light is concentrated and red is conspicuously absent, although as a matter of fact there are two very faint red lines in the mercury spectrum.

AUTOMATIC CONTROL OF ARCS

Lamps used for projection purposes are usually manually operated (i.e. the arc is struck and the length kept to a

constant value by hand), while lamps used for illumination purposes and for photography are automatic in operation. Owing to the decline in the use of arc lamps for general purposes, automatic control of lamps and arc lamp mechanism must be regarded as of diminishing importance, and space allows of a brief outline only of the principles and methods employed.

A very simple arrangement for automatically striking an arc and feeding the carbons forward as they are consumed is shown in Figure 220, where C_+ and C_- are the carbons and I_1 and I_2 are two iron plungers working in conjunction with the fixed solenoids Sh and Se. It will be seen that Sh is a coil arranged in shunt with the arc while Se is a coil arranged in series with the arc. The two carbons are connected together by a flexible and insulating cord F which passes over the pulley W. The moving portions carrying the carbons are weighted so that when no voltage is applied to the lamp the ends of the carbons are brought into contact by the action of gravity.

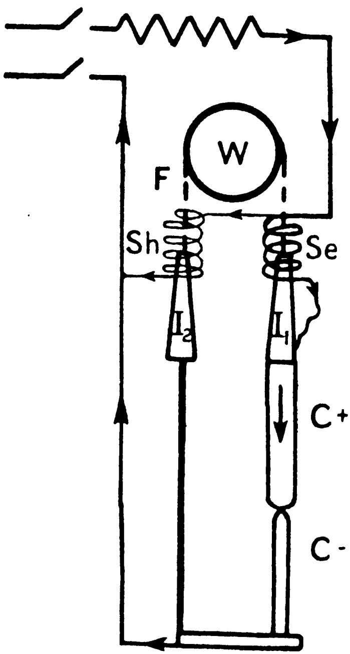


FIG. 220.

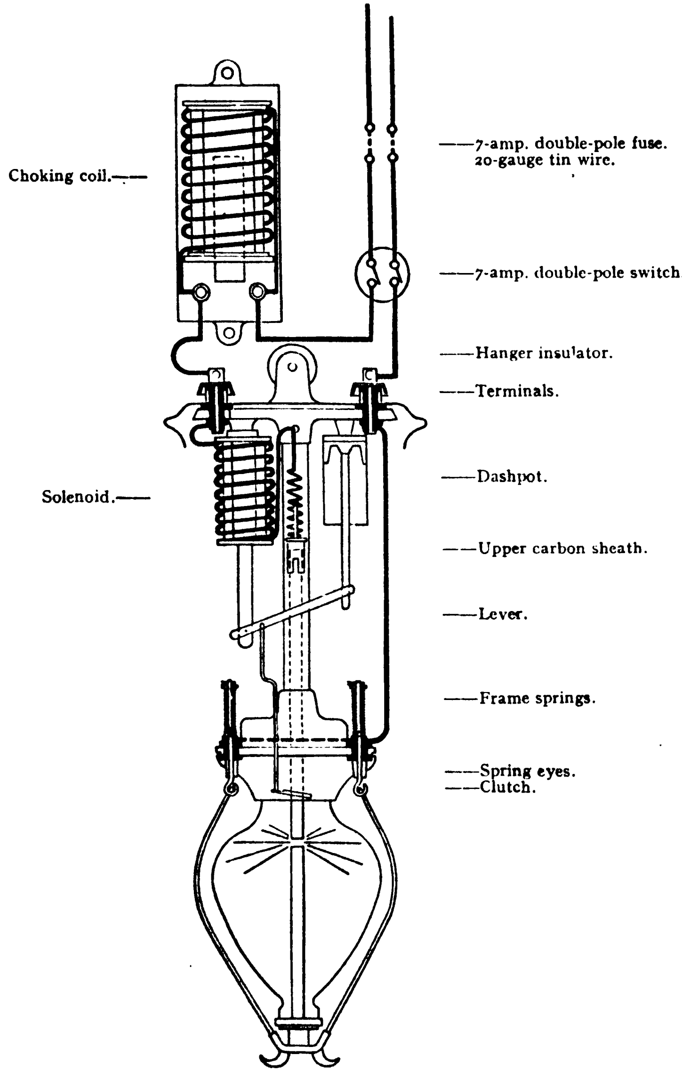
When the switch is closed the momentary current through the series coil is high (since the carbons are actually in contact), while the voltage across the shunt coil is very small, with the result that the top carbon is lifted (the bottom carbon dropping) and the arc is struck. As soon as this has occurred, the pull due to the series coil, which always tends to separate the carbons, falls off, while the pull due to the shunt coil, which always tends to bring the carbons into contact, increases and a position of equilibrium is quickly obtained which gives an arc of suitable length.

As the carbons burn away, the current will tend to fall while the voltage across the arc (and across the shunt coil) will rise and the carbons, due to the changes in the pulls of the two coils, will move nearer to each other thus maintaining a length of arc which is approximately constant. If the lamp is switched off the carbons run together due to the gravity control, and are then ready for the re-starting of the arc when the switch is next closed.

In the arrangement described above, two coils (with opposing effects) are used, giving rise to what is known as a differential type of lamp. It is possible, however, by slight modifications in the arrangements, to use one coil only, either series or shunt, to control the lamp. Further, in order to maintain the arc in a constant position as the carbons burn away, it is usual to use a positive carbon having a considerably larger area of cross-section than the negative carbon, thus producing what is known as a focussing type of lamp.

The above very simple arrangement was actually used in early automatic lamps, but it had serious disadvantages. In the first place, only short carbons, giving short burning time per trim, could be used because it is clear that the iron plungers must not be allowed to move very far or they will get out of range of the pull of the solenoids. Again, since no dashpot is used, the unrestrained pull of the solenoids may give rise to violent movements of the plungers which will cause unsteadiness in the arc. In order to allow of the use of longer carbons, it is usual in practice to provide an intermediate mechanism between the plungers and the carbons, the object aimed at being to keep the plungers in an approximately constant position relative to the solenoids as the carbons are fed continuously forward. Many very interesting arrangements have been evolved for the necessary intermediate mechanism, perhaps the most common types being the brake wheel arrangement (much used for differential focussing lamps), and the clutch arrangement (much used for enclosed lamps controlled by a single series coil).

Neither the space available nor the present-day importance of the subject permits of any considerable description of arc lamp mechanism, and the only example which we shall examine is the clutch mechanism of the Jandus enclosed lamp which has been largely used.



Choking coil.
7-amp. double-pole fuse.
20-gauge tin wire.
7-amp. double-pole switch.
Hanger insulator.
Terminals.
Dashpot.
Solenoid.
Upper carbon sheath.
Lever.
Frame springs.
Spring eyes.
Clutch.

FIG. 221.

A diagrammatic view of the lamp as made for use with alternating currents is given in Figure 221. The various parts are named by the side of the figure, the block for which has been loaned to us by Messrs. Drake & Gorham, to whom we are also indebted for information as regards the working of the lamp.

The current from the mains passes through the choking coil to the lamp terminals, thence through the series coil and by means of the flexible wire to the upper carbon sheath and carbon. The current then passes through the arc to the lower carbon and carbon holder (which are fixed in position), and finally through the globe frame to the other terminal of the lamp.

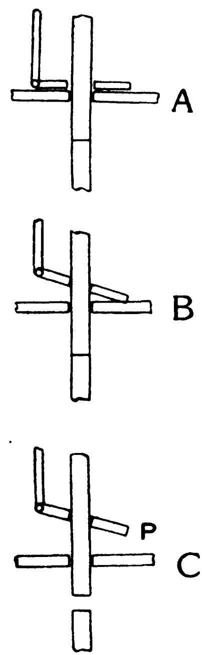


FIG. 222.

The choking coil consists of a number of turns of wire wrapped round a former, in the interior of which slides a laminated iron core. The voltage across the arc may be adjusted by sliding the core in or out.

The most important feature, from our point of view, is the way in which the simple series coil strikes the arc and causes the upper carbon to be fed forward as it is consumed. The clutch, by which the upper carbon is gripped, simply consists of a washer having a hole in it slightly larger than the diameter of the carbon, so that when the clutch is horizontal the upper carbon slips down until it meets the lower carbon, owing to the action of gravity; but when the clutch washer is inclined it grips the carbon, and the two move as one.

When no current is passing through the lamp, the plunger is not pulled up by the series solenoid, and the clutch washer rests in a horizontal position as shown at A in Figure 222. The upper carbon is then in contact with the lower one.

When the switch is closed the plunger is pulled up by the coil, thus tilting the lever to which it is connected; this in its turn causes the washer to assume an inclined position until it grips the upper carbon as shown at B in Figure 222.

As the plunger continues to be pulled up into the solenoid, the washer and upper carbon are raised bodily upwards as at C in the same figure, thus striking the arc.

As soon as the arc is struck, the current, and consequently the pull due to the series solenoid, falls off, and the arc takes up such a length that the upward pull on the plunger due to the solenoid and the downward pull due to gravity balance each other.

As the carbons burn away and the arc gets longer, the pull due to the series coil decreases somewhat, and the plunger moves downward (for a given current the pull on the plunger increases as it goes downward between certain limits, and therefore as the current falls off, owing to the arc becoming longer, the plunger is no longer in equilibrium in its old position, but descends to a new one). This movement causes the clutch washer and upper carbon to move downwards, thus feeding the upper carbon in the desired direction.

This, however, only goes on until the end P of the washer comes in contact with its stop; after this point is reached, any further downward motion of the plunger causes the washer to become more nearly horizontal, thus causing it to lose its grip of the upper carbon, which slips down.

If the mechanism is working well, the carbon will probably only slip down a short distance before being again gripped by the clutch, but sometimes the upper carbon slips down until it meets the lower one, and the arc is struck afresh. This of course momentarily disturbs the steadiness of the light, but as it only occurs once in 4 or 5 hours it is not of great importance.

THE "EDISWAN" POINTOLITE LAMP

This lamp may be regarded as a D.C. Metal Arc, entirely enclosed in a sealed glass globe, in this respect resembling an ordinary incandescent lamp. As the electrodes do not wear away appreciably, no "feed" is required, but the arc must be struck without preliminary contact between them, and in the method of solving this problem lies the most novel and interesting feature of the lamp.

In Figure 223 T is a globule of fused tungsten about $\frac{1}{10}$ inch diameter, connected through a resistance R to the positive supply main. The "normally off" switch K enables the

ioniser circuit to be closed temporarily through a part of the resistance R in order to set up the ionisation required to start the arc.

This globule is very close to the " ioniser," which extends between the wires A and B. Part of this is wound into a helix I, the other half being straight, and enclosed in a small shielding tube S. The ioniser itself is made of refractory

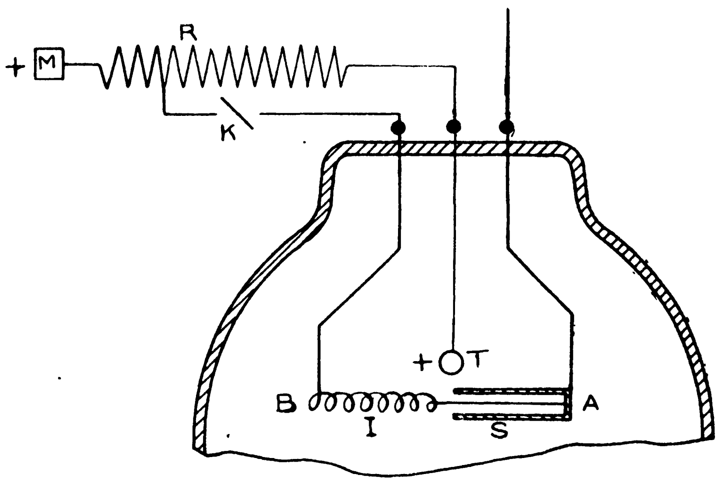


FIG. 223.

materials found to be most suitable for the liberation of negative electrons.

This forms a conducting path initially in circuit with the mains through a portion of the ballast resistance R.

The whole arrangement is sealed into a glass bulb containing sufficient nitrogen to make the gas pressure inside the lamp about equal to the external atmosphere pressure when the lamp is hot.

On first closing the circuit by means of the " normally off " switch K a current flows through the ioniser, heating the helix to incandescence.

The hot helix gives off negative electrons freely, thereby " ionising " the surrounding gas and making it temporarily

a partial conductor. Almost instantly the gap between the globule and the helix becomes sufficiently conducting to permit a current to pass and thus an arc is formed between the globule and the helix when the switch K is released, thus opening the ioniser circuit. In the 100 c.p. type the momentary ionising current is about 6½ amperes, which becomes 1·3 amperes when the arc is running at normal efficiency, the voltage across the gap being 50. These actions take place so rapidly as to be almost instantaneous, and the globule becomes an intensely heated point source of light. That portion of the helix which forms the negative side of the arc would gradually deteriorate with use, and the protecting tube is introduced to prevent this.

The supporting stem for the globule T is made of bi-metal strip, which, owing to the differences in the thermal co-efficients of expansion of the two metals used, bends a little when heated. When the lamp is cool the globule is opposite the helix I, but when the lamp is lit up the globule quickly moves so that it becomes opposite to the tube S which then forms the negative electrode of the arc. The lamp is an illustration of the fact already stated, that an arc can only form by ionisation when the negative electrode is hot and, while it does not matter whether the positive electrode is hot or not at starting, after the arc is struck the positive electrode becomes the hotter and gives out most of the light. These lamps are very useful whenever a point source of white light is required as in lantern work or in micro-photography.

LAMPS USING GAS OR VAPOUR AS THE RADIATING BODY

A number of types of lamps using radiation from a gas or vapour have been introduced in recent years, and though they are perhaps not of great service for general illuminating purposes they have, as a rule, certain properties which render them of great utility for special services. The more important forms are considered briefly below.

The Mercury Vapour Lamp.—This lamp is practically a long vacuum tube with a mercury cathode and iron anode, and at present is only suitable for direct current circuits.

It is shown in Figure 224, where C is the cathode, B the cup-shaped iron anode, and A the ballast resistance, which

in this case is an ordinary wire coil, similar to those used in connection with arc lamps.

It is suspended in the position shown, so that all the mercury is contained in the lower bulb and is started by tilting the tube, either by hand or automatically with the aid of solenoids, until a stream of mercury runs down the tube and momentarily short-circuits the terminals, for in the normal state it is

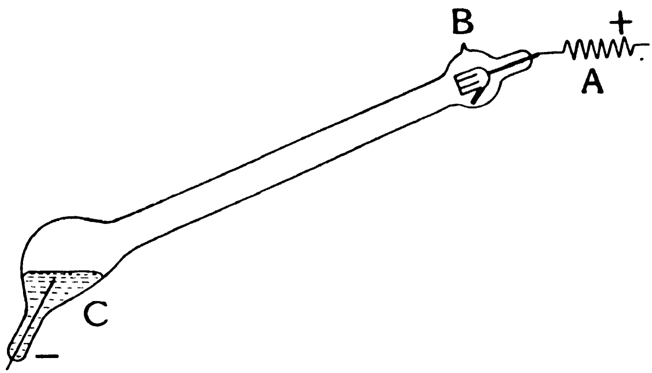


FIG. 224.

quite non-conducting to the working voltage. After tilting, the lamp is allowed to resume its normal position and an arc is struck as the mercury leaves the iron electrode. To facilitate this operation one section of the cup-shaped hollow iron anode is bent downwards so as to nearly touch the glass.

The length and diameter of the tube are determined by the working voltage and current respectively, and tubes about an inch in diameter and two or three feet in length are employed.

A ballast resistance is again necessary, partly to prevent a rush of current at starting, and partly because a gaseous conductor has no definite resistance in the ordinary meaning of the term.

In this case the luminous body is a gas, i.e. mercury vapour, and not an intensely heated solid ; herein lies the fundamental distinction between this type of lamp and those already

described. As a consequence the laws of radiation already outlined do not apply. High temperature alone does not usually make a gas luminous, whereas it may become very luminous without much rise of temperature if made to carry an electric current, by taking advantage of the fact that a gas under reduced pressure conducts moderately well. Hence the lamp resembles an ordinary vacuum tube; but without the mercury it would require a much higher voltage, take a very much smaller current, and give out much less light. The presence of the readily volatilised mercury really turns it into something intermediate between a vacuum tube and a long mercury arc working under reduced pressure. Mercury is not in itself essential—other substances would work at first, but it is the only available substance which can be vaporised and condensed again without forming objectionable deposits on the glass.

The effective resistance of the lamp is very much greater when the direction of the current is reversed, and for practical voltages it acts as a kind of valve which only allows a current to flow one way. Hence it is also possible to use it as a rectifier for alternating currents. This difference in conductivity in different directions is a characteristic property of gaseous conduction, but to discuss its full significance would lead us too far from our subject.

A gaseous conductor possesses the initial advantage that the energy supplied can usually be expended on a very small amount of active material, but on the other hand it has the distinct disadvantage that it radiates only certain kinds of light; in other words, it gives a "line" spectrum and not a "continuous" spectrum.

That of the Cooper-Hewitt lamp is shown in Figure 219, Plate X. It is, of course, the spectrum of mercury, and consists essentially of two yellow lines close together, a very strong green line, a strong blue line, and two violet lines. The resulting illumination is a ghastly kind of bluish-white light, but there is very little red in it, so that it makes red objects look black, whilst accentuating every trace of green.

The lamp is very efficient, but attempts to introduce red rays into the light have not been very successful and the lamp is not greatly used for illuminating purposes. The emission from the lamp is very rich in ultra-violet rays and is

particularly suitable for meeting photographic requirements. The ultra-violet rays from this type of lamp are also used for medicinal purposes and for this work it is necessary to use a tube of quartz instead of glass, since the latter cuts off a large proportion of the rays required. When using such medicinal lamps it is necessary to protect the eyes of the operator and patient, otherwise severe inflammation may result.

The "Moore Tube."—This very interesting method of illumination is an application of the familiar "vacuum tube," used to illustrate the luminous effects obtained when a discharge is passed through gases at low pressures. The "lamp" is a very long (sometimes 70 metres) vacuum tube, built up in the room to be illuminated by welding together lengths of glass tubing. The tube contains nitrogen when a reddish light is desired, and carbon dioxide for a fairly white light.

The vacuum tube thus produced takes 0·3 ampere at about 12,000 volts, supplied from A.C. mains by means of a special type of transformer. The method is excellent in principle, for it undoubtedly produces light without necessarily producing much useless heat, and the efficiency of the tube itself is very high, although the unavoidable losses in the transformer, choking coils, etc., lower the all-round efficiency to something like 8 lumens per watt. On the other hand, the use of high voltages, and the difficulty in repairing breakages, are serious objections.

The "Neon Tube."—This is similar to the Moore light, but the tubes contain the rare gas Neon. The tubes are 6 metres long and are operated at about 1000 volts from A.C. mains by transformers. They give about 900 mean spherical C.P. at about 14 lumens per watt, including transformers and other losses. The colour of the light is extraordinary, being of a beautiful orange, and is entirely lacking in blue rays.

The "Osglim" Lamp.—Moore and Neon tubes have the disadvantage of requiring voltages higher than those usual in lighting circuits, but the General Electric Co., by choosing a suitably small distance between the electrodes and by using Neon gas at an appropriate pressure, have brought out a lamp of the gas radiator type which can be used on circuits of ordinary voltage. The electrodes are of stout metal and the lamp cap (which contains a ballast resistance) is of the

ordinary B.C. type. The lamp, which in the standard size absorbs 5 watts only, is suitable for night lights and for electric signs. When used for the latter purpose, the cathode can be made in the form of letters or figures which, when the lamp is lit, appear to be surrounded by the characteristic orange glow. The peculiar characteristics of the Osglim lamp also make it useful for many purposes in scientific investigations.

ILLUMINATION

Illumination may be described as the art of using lamps, and it is clear that electric or other types of lamps will not give the maximum satisfaction unless they are correctly used. The essentials of a satisfactory scheme of illumination are as follows:

(1) The colour should approach that of daylight as nearly as possible.

(1) Absence of glare due to direct views of bright filaments.

(3) Adequate intensity of illumination.

(4) Reasonable uniformity of intensity of illumination over the area considered.

(5) Steadiness.

Colour of Light.—Our eyes have been developed under the influence of the sun and so respond most satisfactorily to an artificial light which has the same characteristics of colour. The point may be of particular importance in certain cases, as in drapery shops, dye-houses and other places in which colour matching has to be effected. Artificial lights have, as a rule, too large a proportion of red rays and, when necessary, it is possible to provide filament lamps with glass so tinted as to absorb a larger proportion of rays near the red end than of rays near the blue end of the spectrum. In daylight such glasses appear to be of a blue or green tint.

Absence of Glare.—The object of true illumination should not be to throw rays directly into the eye, but on to the object which is to be viewed, from which they will be reflected into the eye. If the intense rays from an unshaded filament impinge directly on the eye, a certain eye-strain will be felt and the objects which it is desired to illuminate will be less

clearly seen. One method of preventing glare is to use indirect illumination in which the rays from the lamps are thrown on to a light-coloured ceiling from which they are reflected downwards. A more usual way is to provide the lamps with reflectors or shades which, to a large extent, prevent a direct view of the filament, and, at the same time, reflect in a downward and more useful direction any rays

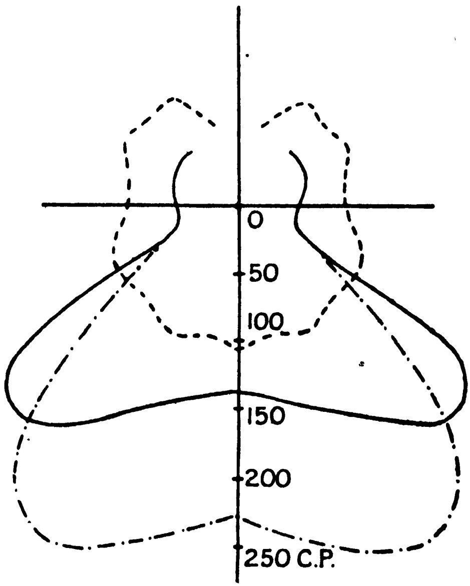


FIG. 225.

which would normally tend to go in directions above the horizontal plane through the centre of the lamp. For industrial purposes reflectors are often made of metal coated with white enamel on the inside, while for other purposes, shades, globes, and bowls made of moulded glass or other suitable material are common. When choosing a reflector it is important to realise that a choice can be made from a wide range of types. Certain types are most suitable when a concentrated downward beam is required, thus the chain

line in Figure 225 represents the distribution produced by what is known as an intensive reflector. Other types are most suitable when a more widely diffused beam is required, and the continuous line in the same Figure represents the distribution produced by an extensive reflector. The dotted line shows the distribution produced by the lamp alone.

In modern gas-filled lamps the intrinsic brilliance of the filament is much greater than in vacuum-type lamps and this fact has led to the introduction of the " Pearl " type of bulb as a means of diminishing glare. The table of intrinsic brilliances given below indicates the importance of adequate shading of modern light sources. The data in this table and the material used in making Figure 225 have been kindly supplied by the Holophane Company.

Intrinsic Brilliancy of Light Sources

Light source.	Candle power per square inch.
Moore tube	0·3 to 1·75.
Blue sky	2·0.
Candle	3 to 4.
Flat gas flame	3 to 8.
Oil lamp	3 to 8.
Frosted tungsten vacuum lamp	10.
Gas mantle (low pressure inverted)	50.
Gas mantle (high pressure)	300.
Carbon filament	375 to 480.
Tungsten filament (vacuum)	1000.
Oxyhydrogen limelight	5000.
Flame arc	5000.
Tungsten filament (gas-filled lamp)	5250.
Sun at zenith	600,000.

Intensity of Illumination.—The magnitude of the illumination on a surface is measured by the amount of luminous flux reaching the surface per unit area. The unit is called the foot-candle and is the illumination produced by a source whose intensity is one C.P. on a surface (placed normally to the rays) at a distance of one foot. If we imagine a sphere of one foot radius placed round a source giving an intensity of one C.P. in all directions, the total luminous flux emitted

will be 4π lumens and this will be distributed over 4π square feet, and we see, therefore, that an illumination of one foot-candle may also be expressed as an illumination of one lumen per square foot. If we imagine the sphere of one foot radius replaced by another sphere having a radius of D feet, the area of surface of the new sphere will be $4\pi D^2$ square feet and, since the total luminous flux will be unaltered, the illumination on the surface of the new sphère will be $\frac{4\pi}{4\pi D^2}$ $=\frac{1}{D^2}$ lumens per square foot or foot-candles. Or, in general, we may say that the illumination due to an intensity of light C.P. on a surface normal to the rays at a distance of D feet will be $\frac{C.P.}{D^2}$ foot-candles.

Often the incident rays will not be normal to the surface, and this will result in the same amount of light flux being spread over a larger area, thus giving a lower value of illumination. In Figure 226 it will be clear that when the rays are normal to the surface a certain number of lumens will be spread over a surface whose area is proportional to AB, while if the rays are incident on a surface (situated at the same distance from the source), making an angle ϕ with the first surface, the same number of lumens will be spread over an area proportional to BC.

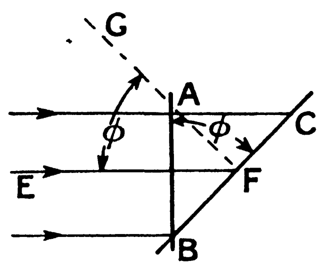


FIG. 226

$$\therefore \frac{\text{Illumination on surface normal to the rays}}{\text{Illumination on surface inclined at } \phi^\circ \text{ to normal surface}}$$

$=\frac{BC}{AB}$, or illumination on inclined surface is equal to illumination on normal surface $\times\frac{AB}{BC}=\frac{\text{candle power}}{D^2}\times\cos\phi$ when ϕ is the angle between the rays and the normal to the surface (i.e. the angle EFG).

Oftentimes the illumination on a surface will be due to more than one source; and in such cases the illumination due to each source may be calculated and the total illumination found by addition.

Example.—Two lamps, each giving 100 C.P. in all directions below the horizontal plane drawn through the centre of the lamp, are situated 10 feet apart and 8 feet above the horizontal working plane. Determine the illumination on the working plane (*a*) at a point immediately under one of the lamps, (*b*) at a point half-way between the two lamps. Illumination at C (see Figure 227)

$$=\frac{\text{C.P.}}{\text{AC}^2}+\frac{\text{C.P.}}{\text{BC}^2}\text{ Cos ACB}=\frac{100}{8^2}+\frac{100}{8^2+10^2}\times\frac{8}{\sqrt{8^2+10^2}}$$

$= 1{\cdot}563 + 0{\cdot}381 = 1{\cdot}944$ foot-candles.

$$\text{Illumination at D} = 2\times\frac{\text{C.P.}}{\text{AD}^2}\text{ Cos ADF} = 2\times\frac{100}{8^2+5^2}\times\frac{8}{\sqrt{8^2+5^2}}$$

$= 1{\cdot}905$ foot-candles.

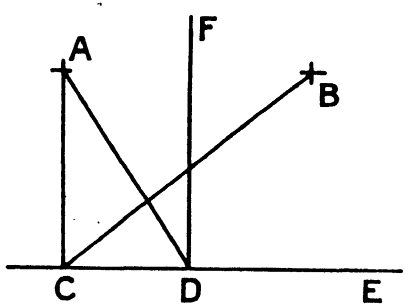


FIG. 227.

The intensity of illumination desirable in any case depends largely on the purpose for which the illumination is required, and it may be noted that intensities of illumination considered necessary at the present time are far higher than those used for similar purposes in the past. The numbers in the following table, which is included by permission of the Holophane Co., Ltd., may be taken as representative of present-day requirements.

Object of illumination.	Desirable value of illumination in foot-candles.
Drawing Office.	10·0 to 15·0
Factory, General illumination.	3·0 to 4·0
Local bench illumination.	8·0 to 10·0
Local bench, fine work.	12·0 to 15·0
Reading Room.	4·0 to 6·0
Museum.	4·0 to 6·0
Power House.	4·0 to 6·0
Residence, Porch.	0·5 to 1·0
Entrance Hall.	1·0 to 3·0
Drawing Room.	3·0 to 4·0
Dining Room.	4·0 to 6·0
Kitchen.	3·0 to 4·0
Bedroom (General).	1·0 to 2·0
School, Class Room.	4·0 to 6·0
Corridor.	1·0 to 2·0
Warehouse.	1·0 to 3·0
Wharf.	0·5 to 1·0

Uniformity of Illumination.—On the whole it is desirable that the intensity of illumination in a room should be reasonably uniform throughout, since this state of affairs tends to minimise eyestrain. In the eye is situated a diaphragm, known as the iris, and, as the amount of light tending to enter the eye varies, this diaphragm opens and closes automatically in an endeavour to minimise the variations. In an area in which the illumination is irregular, the diameter of the diaphragm will be constantly undergoing adjustments as objects of varying degrees of brightness are viewed and, since the diaphragm is rather sluggish in action, eyestrain is likely to result. In practice it is, of course, not possible to secure absolutely uniform illumination over an area, and if the ratio $\frac{\text{maximum illumination}}{\text{minimum illumination}}$ does not exceed 2, the illumination may be regarded as sufficiently uniform for practical purposes.

Steadiness of Illumination.—Little trouble is experienced in this respect with filament lamps so long as the supply voltage is reasonably constant. Arc lamps, however, give a little trouble at times when the mechanism is not working smoothly.

Mode of Design of Provisional Schemes to provide Uniform Illumination.—The formula given on page 363 is very useful for checking the illumination at any point when the spacing and distribution of C.P. from the lamps is known, but, when provisionally arranging a scheme, the method given below is more useful. Having ascertained the floor area of the room, a decision must first be made as to the number of lamps to be employed. The desired illumination can, of course, be obtained either by a small number of lamps of high power or a larger number of lamps of smaller power. The height of the room will be a factor in making this decision, a low-pitched room favouring the use of a large number of small units. The floor area should next be divided into a number of equal squares (so far as the shape of the room will allow) with a view to placing one lamp above the centre of each square. A suitable value for the illumination having been chosen (see the table on page 365), the useful output from each lamp (expressed in lumens) can be obtained. To obtain the total output from each lamp, the useful output must be divided by a utilisation factor and by a lamp depreciation factor, the magnitudes of both of these being settled by experience.

The utilisation factor is the ratio of the portion of the output from the lamp which is usefully used to the total output, and its value will depend primarily on the nature of the walls and ceilings of the room and upon the type of reflector in use. Some typical values are given in the following table for which the writer is indebted to the Holophane Company.

COEFFICIENTS OF UTILISATION

Ceiling	Light			Medium	Dark
Walls	Light	Medium	Dark	Medium	Dark
Type of reflector					
Holophane	·66	·62	·54	·54	·43
Holophane, Semi-indirect .	·49	·45	·41	·41	·32
Holophane, Indirect . .	·33	·30	·26	·20	·10
Bare lamps . . .	·43	·37	·31	·31	·23

The lamp depreciation factor is to allow for the falling off in output of the lamps as they age, thus causing an illumination which was initially satisfactory to fall below the requirements at a later period. It may also be used to allow for loss of efficiency of the shades due to dust or other causes. Suitable magnitudes for the depreciation factor are likely to lie between 0·85 and 0·75. The total output per lamp having been ascertained, the correct size of lamp may be found from a table of lamp outputs, such as the one given below, which has been extracted from the lists of the General Electric Company. The particulars refer to lamps for voltages of 200–260, the lamps being gas-filled except in the case of the 25-watt size.

Input of lamp. (Watts)	Output of lamp (approx.). (Lumens)
25	198
40	332
60	594
75	803
100	1,160
150	1,875
200	2,600
300	4,140
500	7,500
1000	16,900
1500	27,000

The height of the lamp above the working plane must next be decided with a view to securing the most uniform result. This distance will depend upon the type of reflector used and, when this has been chosen, it will be well to use the value for $\dfrac{\text{Height above working plane}}{\text{Horizontal distance between lamps}}$ recommended by the makers of the reflectors employed, since the value of this ratio will depend upon the distribution of intensity produced by the reflector in different directions.

In the absence of more precise information the value of the ratio may be taken as from $\frac{1}{2}$ to $\frac{2}{3}$, though for a few types of reflectors the value may approach unity.

Example of Provisional Method of Design.—It is required to produce on the working plane (situated 3 feet above the

floor) of a room whose floor area measures 80 feet by 40 feet, an average illumination of 5 foot-candles. If the walls and ceilings are of light colour, choose a suitable number and size of lighting units if direct lighting is used.

The floor space divides readily into 8 squares each having a side of 20 feet and, if we decide to use 8 lamps, the number of useful lumens from each must be $20 \times 20 \times 5 = 2000$.

Taking a utilisation factor of 0·66 and a lamp depreciation factor of 0·8, the total output per lamp will be $\frac{2000}{0{\cdot}66 \times 0{\cdot}8}$ $= 3800$ lumens (approx.), and the nearest standard size of lamp is the one with an output of 300 watts.

The height above the floor should be $\left(\frac{2}{3} \times 20 + 3\right) = 16$ feet, and the positions of the lamps are shown in Figure 228.

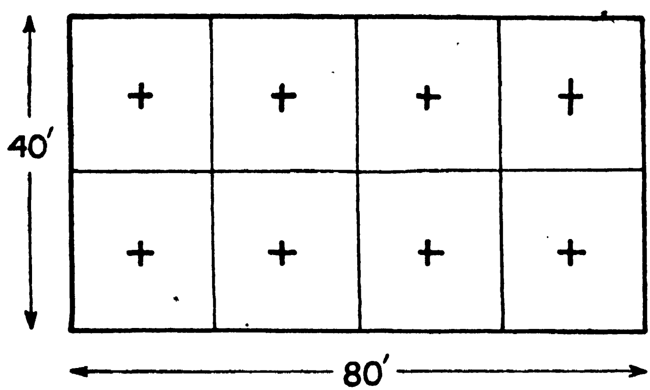


FIG. 228.

CHAPTER XIV

MEASURING INSTRUMENTS

THE measurement of the three primary quantities, E.M.F., current, and resistance, is of fundamental importance to the electrical engineer, for on such measurements is more or less directly based the further determination of power, energy, etc. It is therefore desirable, without attempting to deal with the subject exhaustively, to indicate the principles underlying the construction and use of certain instruments.

Galvanometers, ammeters, and voltmeters have been frequently referred to in the preceding pages. These names should suggest differences in detail, not in kind. Every galvanometer is a possible voltmeter or ammeter, and every voltmeter and ammeter either is, or may be used as, some form of galvanometer. Althought the latter word literally means a " measurer," the term has gradually come to signify any instrument intended to indicate merely the existence of a current without necessarily measuring its strength; of especial interest and value being those forms which are intended to indicate extremely minute currents.

It is possible, in many varied ways, to apply the heating or magnetic properties of a current in such a manner as to obtain motion of a pointer over a divided scale. For instance, we may use a pivoted compass needle inside a coil of wire, as in the earliest and simplest form of galvanometer, or a pivoted or suspended coil in a magnetic field as already described, or the heating effect of the current may produce expansion and hence movement, and so on.

The instrument thus produced contains a conductor of some kind—perhaps a coil of wire, perhaps a thin wire for expansion—through which the current must pass in order to

produce a deflection, i.e. once made it has a definite resistance, great or small. This instrument, whatever its nature, we may term a "movement," and so far it constitutes some form of galvanometer. Different currents will produce different deflections, and usually all we can say is that a larger deflection means a larger current, but how much larger is uncertain. If now we calibrate it in some way, say by sending currents of known strength through it and marking the positions of the pointer to correspond, it becomes a kind of ammeter; and if instead of the values of current we mark the value of the P.D. between the terminals (i.e. the product $I \times R$, where R is the resistance of the instrument), it becomes a kind of voltmeter, but these terms really imply something more. They suggest not only direct reading instruments such as the above would be, but also very low resistance in the case of an ammeter and very high resistance in the case of a voltmeter.

Very probably the winding of our movement has necessarily a fairly high resistance to start with. This, however, does not invalidate its use as an ammeter.

Whatever the principle of the movement may be, and whatever its resistance, it can be used as an ammeter in the true meaning of that term if it be provided with a shunt or by-pass of low resistance and sufficiently thick to carry the current without undue heating. The actual working range is then determined by the resistance of the shunt, and is at our disposal. To take a simple example, suppose the movement itself has 10 ohms resistance, and it is found by trial that a current of $\frac{1}{10}$ ampere, i.e. a P.D. of 1 volt between the terminals, deflects the pointer to the fullest extent. Now, let it be shunted with a stout conductor of $\frac{1}{1000}$ ohm resistance, and it becomes at once an ammeter reading up to 1000 amperes. (To obtain exactly the same deflection in the two cases it is evident that the *combined* resistance of the movement and shunt should be $\frac{1}{1000}$ ohm.) Similarly, if the combined resistance of shunt and movement be $\frac{1}{100}$ ohm, the full deflection means 100 amperes and so on.

If a voltmeter is required, instead of shunting the movement, a suitable resistance, wound non-inductively and placed out of the way inside the case, is put in series with it; for instance, in the above case, if the added resistance is 990 ohms,

so that the total is 1000 ohms, the full deflection is obtained with a voltage of 100, and the instrument becomes a voltmeter reading up to that limit.

In these examples we have assumed the working current in the movement, i.e. the current required to give a full deflection, to be $\frac{1}{10}$ ampere. The exact value will depend upon the type of instrument: in some it is possible to obtain greater sensitiveness than in others, and it is a matter of real importance. It will become apparent that the smaller the working current is, the more nearly the completed instrument approximates to the ideal standard of infinitely great resistance in the case of a voltmeter and infinitely low resistance in the case of an ammeter.

This question of resistance is not always clearly understood by students. It is not that any departure from the general rule will necessarily cause inaccuracy in the readings themselves; the real trouble is that the current or P.D. to be measured may be seriously altered in amount by merely connecting up the instruments intended to measure them.

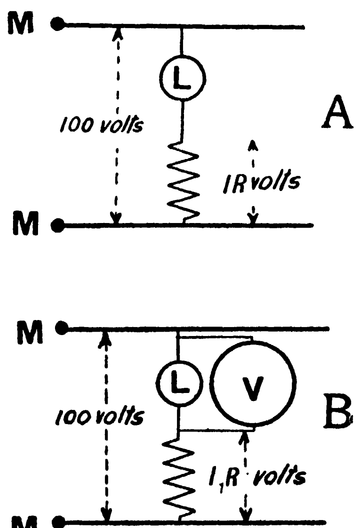


FIG. 229.

To make the point clear, consider the following example:

A 90-volt lamp in series with a resistance is placed across 100-volt mains. On connecting a voltmeter across the lamp terminals to ascertain whether the voltage is correct, the light diminishes.

Figure 229 (A) shows the arrangement. Evidently the value of R is such that it absorbs 10 volts, or $I \times R = 10$, leaving 90 volts across the lamp as required. Now the only way in which the current through the lamp can alter is by an alteration in the P.D. across it. Hence if the light does diminish as stated when

the voltmeter is connected, it is because the presence of the instrument has in some way lowered the voltage it is intended to measure. Figure 229 (B) helps us to see how this comes about. Let R_l=resistance of lamp, R_v=resistance of voltmeter, and R=resistance in series with lamp.

Then in (A) total resistance is R_l+R, and $I=\dfrac{100}{R_l+R}$

But in (B) total resistance is $\dfrac{R_l \times R_v}{R_l+R_v}+R$, and this is less than before, because the resistance of lamp and voltmeter in parallel is less than that of the lamp alone. Therefore the new current I_1 is greater than I. But if in the first case $I \times R=10$, then in the second case $I_1 \times R$ must be greater than 10, and the P.D. across the lamp consequently less than 90 volts. Hence the current through the lamp is less than before and the light diminishes.

In this example notice that so long as the resistance of the voltmeter is not infinitely large this effect must occur to some extent, becoming smaller the greater the resistance of the voltmeter, and vanishing completely if the latter is infinite, i.e. in an electrostatic instrument; but in all cases the voltmeter may measure perfectly correctly the actual P.D. when the instrument is connected.

Still further, to show the serious errors that may be made in practice if instruments are used without due consideration, consider the following results (taken from a student's notebook).

In order to measure the resistance of an incandescent lamp when hot, it was connected up as shown at A in Figure 230 to the mains.

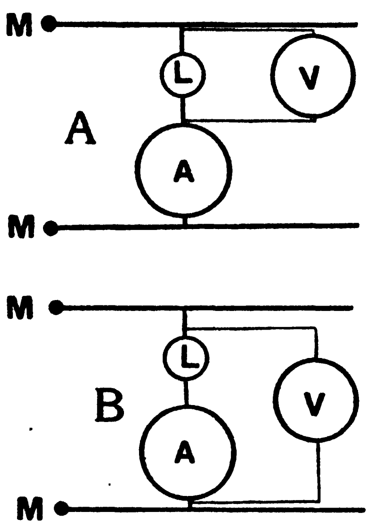


FIG. 230.

Readings were $V = 103$ volts.
$I = 0 \cdot 825$ ampere.

$$\text{Hence } R_l = \frac{V}{I} = \frac{103}{0 \cdot 825} = 125 \text{ ohms.}$$

Now the point is that such a result might be accepted as correct, whereas it will only be correct if the resistance of the voltmeter is very great compared with that of the lamp, that is, if the current through the voltmeter is exceedingly small compared with that through the lamp.

The diagram shows that the current as read does not all pass through the lamp, and a little consideration will show that what has really been measured is the joint resistance of the lamp and voltmeter in parallel.

$$\text{That is } \frac{R_l \times R_v}{R_l + R_v} = 125 \text{ ohms.}$$

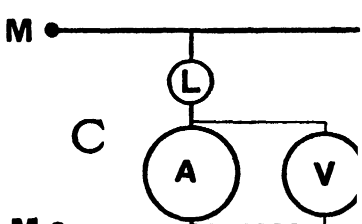
The connections were then altered to those shown in Figure 230 at B, the new readings being—

$V = 106$ volts.
$I = 0 \cdot 655$ ampere.

$$\therefore R_l = \frac{V}{I} = \frac{106}{0 \cdot 655} = 162 \text{ ohms.}$$

This result has equally good claims to be considered the resistance of the lamp. Really it is the resistance of the lamp and ammeter in series, or $R_l + R_a = 162$ ohms, and will be near the true value if R_a is, as usual, fairly small, but will only be absolutely correct if $R_a = 0$.

The next step was to connect up as in Figure 231 at C (for this purpose a lower reading voltmeter was required).



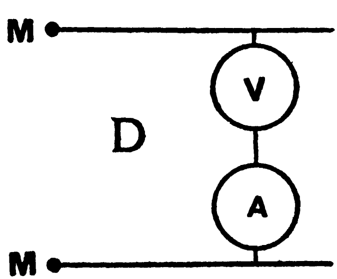


FIG. 231.

Here we get equally correctly the current through the ammeter and the voltage across it, the readings being—

$$V=0{\cdot}5 \text{ volt}, \ I=0{\cdot}59 \text{ ampere.}$$

$$\therefore \ R_a=\frac{V}{I}=\frac{0{\cdot}50}{0{\cdot}59}=0{\cdot}85 \text{ ohm.}$$

Hence from the previous result the actual resistance of the lamp is $162-0{\cdot}85=161$ ohms (nearly), and therefore the result obtained in the first experiment is seriously inaccurate.

Merely to confirm these results, and not as a practical method of measurement, the resistance of the voltmeter was then obtained approximately by connecting up as at D in the same figure.

This gives the voltage across voltmeter and the current through it.

$$\text{Readings were } V=101$$
$$I=0{\cdot}17$$

$$\therefore \ R_v=\frac{V}{I}=\frac{101}{0{\cdot}17}=594 \text{ ohms.}$$

Now we have obtained already that

$$\frac{R_l\times R_v}{R_l+R_v}=125$$

$\therefore$ substituting from above,

$$\frac{R_l\times 594}{R_l+594}=125$$

$$\text{or } R_l=158 \text{ ohms (nearly).}$$

This agrees with and confirms previous results within reasonable limits.

These examples should show the great practical convenience of making the resistance of a voltmeter exceedingly great, and that of an ammeter exceedingly small. How far it is possible to approximate to the ideal values depends largely upon cost and upon the type of instrument.

As regards type, innumerable varieties have been designed, and almost every possible property of a current has been pressed into service, but the effect of evolution acting under the influence of commercial selection has gradually simplified

matters, and therefore we can say roughly that at the present time there are at least five important and distinct types in general use. Before discussing examples of these it may be worth while to state those properties most desirable in practice. For our present purpose we need not discriminate between portable and switchboard instruments :—

1. They should be "dead-beat." If not, readings are often difficult to obtain on slightly fluctuating circuits, and lack of this property leads at times to much exasperation.

2. They should be mechanically strong and able to stand fairly rough usage without injury or alteration of calibration.

3. They should be unaffected by external magnetic fields. If otherwise, readings may be unreliable near masses of iron or "live" conductors.

4. They should be capable of carrying a moderate overload for a short time, say a few seconds, without injury. This is a point of much practical importance.

5. The scale should be large and the divisions fairly uniform. This depends mainly upon the "law" of the instrument.

6. The insulation of working parts should be good. Obviously this is especially important in a voltmeter.

7. The temperature error should be negligible. This may be serious in certain types of voltmeters, and means that the reading alters when the instrument is left in circuit and gradually warms up. It may also become important in the case of "moving coil" ammeters having coils of copper and shunts of material with negligible temperature coefficient.

8. They should be inexpensive in construction.

9. Their power consumption should be small. This is important in switchboard instruments kept permanently in circuit. It is another way of saying that a voltmeter should have an infinitely high, and an ammeter an infinitely low, resistance.

The types alluded to above are :—

1. Moving coil instruments with permanent magnets. These are for direct current circuits only, and for that purpose probably unsurpassed.

2. Hot-wire instruments. These possess the great advantage of being equally correct on both direct and alternating circuits, and at all frequencies.

3. Instruments with spring control and soft iron moving

parts. These are also useful on both kinds of circuits, but not necessarily correct on alternating circuits except at the particular frequency for which they were calibrated.

4. Electrostatic instruments. The ideal construction for voltmeters, but on account of the small moving force available they are only suitable for high voltages as commercial instruments. For low voltages they are better as delicate laboratory instruments. Strictly speaking they are possible as ammeters if provided with a suitable shunt, but practically only then available as very delicate laboratory instruments.

5. Instruments of the dynamometer type.

This list is not quite exhaustive, but fairly covers modern practice. As regards alternating currents it is obviously essential that the direction of motion should be independent of the direction of the current, but it is perhaps advisable to look into the matter a little more closely. An ammeter or voltmeter on an A.C. circuit is required to indicate the R.M.S. value of the current or voltage as the case may be (see page 230). To do this we need a movement such that the deflecting force, for any one position of the moving parts, is proportional to the square of the current (or voltage). The average deflecting force will then be proportional to the average square of the current (taken over half a cycle) or to the (R.M.S. value)^2. The pointer does not follow the changes in force during a cycle, owing to the inertia of the moving parts, but takes up a position which is dependent on the average force. If we assume, for the moment, that the deflecting force depends only on the (current)^2 and is not dependent on the relative position of the fixed and moving parts, and, further, that the deflection is proportional to the deflecting force (whether these conditions do or do not exist depends on the type of movement and on the type of control), we shall not get a scale giving equal increments of deflection for equal increments of current, but a scale following a square law (i.e. doubling the current quadruples the deflection). This point will need attention when dividing and marking the scale. If we use a movement of the type indicated above on D.C. circuits, the deflecting force will be constant (so long as the current is constant) and there will be no need to use the inertia of the movement to average up the deflecting force during a cycle, but the square law scale will, of course, still be in evidence. In practice,

owing to peculiarities of the movement or of the control, we may not get a perfect square law scale, but the general ideas in regard to the indication of the R.M.S. value, which are outlined above, will still apply. Let us consider how the square law is secured in the moving iron type instrument. The iron is always worked at low flux densities so that the intensity of magnetisation produced in the iron is nearly proportional to the current. Thus, when the current is doubled, the iron is magnetised to double the strength and is situated in a region of magnetic force which is likewise doubled. The mechanical force is quadrupled, thus giving the desired square law. A more exact square law connecting current and deflecting force occurs in instruments of the dynamometer type. Care must be taken with A.C. instruments that the frame and case do not become the seat of eddy currents. To this end all possible closed paths, such as metal bobbins, portions of dial plate, etc., are slit through with a fine saw-cut.

The student should notice that although a good direct-current instrument may not work at all on alternating circuits, simply because the direction of movement is not independent of the direction of the current, every alternating current instrument is bound to give some reading on direct-current circuits (excepting certain induction instruments not dealt with here). Again, it will usually be calibrated either by the use of direct currents or by comparison with instruments already standardised by means of direct currents, because this is the most convenient way in which currents and P.Ds. of accurately known value can be readily obtained. But it does not follow that a given instrument will read the same on both direct and alternating circuits. If it be very non-inductive (such as the hot-wire type), it will do so in all cases and at all frequencies, and hence the special value of such instruments. But if it contain iron in any serious amount, or coils of wire, there will be a choking effect to be reckoned with, which will increase with the frequency.

An ammeter of this kind will read on both circuits fairly accurately, even if the frequency be altered ; but, as a rule, a voltmeter will not, because a given alternating P.D. sends a smaller current through it than the same direct P.D. It must be calibrated indirectly by comparison with an instrument

known to read alike in both cases, and it will then only be accurate at that one particular frequency. It is the especial and conspicuous advantage of hot-wire and electrostatic voltmeters to be absolutely free from difficulties of this kind.

MOVING COIL INSTRUMENTS

These are more or less on the lines of instruments first introduced into practical use by Weston, although the principle of the moving coil itself was first applied by Lord Kelvin in his siphon recorder, and was afterwards developed in the direction of sensitive reflecting galvanometers by D'Arsonval, Ayrton, and many others.

Figure 232, which we reproduce by permission from Carhart and Patterson's *Electrical Measurements*, shows the usual construction, a portion of one of the poles and pole pieces being removed for the sake of clearness.

A steel permanent magnet of the horseshoe type is fitted with soft iron pole pieces, and the circular polar gap is almost completely filled up with a fixed soft iron cylinder, the clearance being very small, from $\frac{1}{16}$ to $\frac{1}{8}$ inch in different instruments. This gives a strong and almost uniform field in the polar gap. Pivoted to turn freely in this gap is a small coil, wound on a metal frame and fitted at each end with spiral springs like watch springs, which determine its zero position and furnish the controlling force. These springs are fixed oppositely, so that when the coil moves one is wound up and the other unwound, an arrangement which eliminates the effect of change of temperature.

The zero position of the coil is near a pair of pole tips, and its range of motion extends nearly to the other pair. As the field is almost constant, the moving force is nearly exactly proportional to the current in the coil, and the latter moves round until the couple due to this force is balanced by the reverse couple due to the twist of the springs. So far the construction is the same for either voltmeter or ammeter; and as already explained in the former case, a suitable non-inductive high resistance will be placed in series with it, and in the latter it will be shunted with a conductor of low resistance and of the necessary carrying capacity.

For direct current work these instruments are excellent,

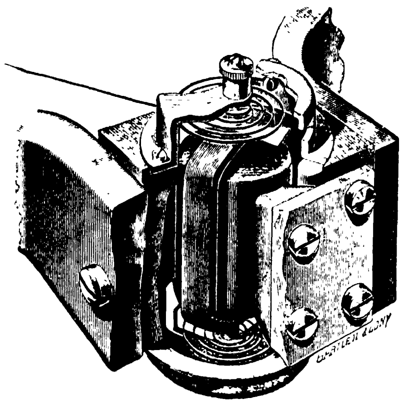


FIG. 232

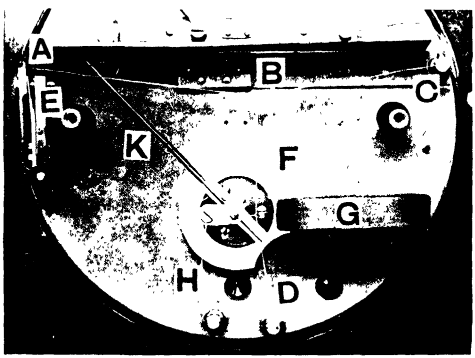


FIG. 233

although useless with alternating currents, because the direction of motion depends upon the direction of the current. It may be urged against them that their accuracy depends on the absolute constancy of the steel magnet, but practically there is little serious trouble in this way. Steel magnets can now be artificially "aged," so that their strength remains the same for an indefinite time.

The special merits of the type are :—

1. The strong field available gives an adequate turning force with a small current. Hence frictional errors are negligible, and exact levelling, etc., immaterial.

2. Since the working current is small, it is possible to make the resistance of a voltmeter very high, and that of an ammeter very small, which means small power consumption.

3. On account of the uniformity of field in the polar gap, the scale is practically uniform throughout the whole range. Further, the instrument is almost unaffected by external fields.

4. The metal frame carrying the coil makes the movement very dead-beat, acting in the same way as the metal tube enclosing the coil of a suspended coil galvanometer (see page 92).

HOT-WIRE INSTRUMENTS

The first of these was the "Cardew" voltmeter, now obsolete. In this instrument the increase of length due to expansion of a fine wire heated by the passage of a current was made use of directly to turn a spindle, the smallness of the expansion necessitating magnification by gearing and the use of a very long wire. As a result the instrument was rather large and clumsy, apart from other drawbacks, and it has been superseded by later forms, using exactly the same principle, but in which the necessary magnification is obtained by a simple device which obviates the necessity for a very long wire. Of such instruments, those made by Johnson and Phillips under Hartmann and Braun's patents may be taken as a type. Figure 233 is from a photograph, taken with scale plate removed. ABC is the "hot wire"; a very thin wire of platinum-silver, about 6½ inches long, tightly stretched between insulated terminals A and C. At A is a spring and screw E by which the tension can be adjusted at any time

from the outside. At some point B is attached a fine phosphor-bronze wire, its other end being fixed to a pin D, and finally a thread of cocoon silk starts from a point near the middle of this wire BD, passes round a pulley on the spindle which carries the pointer, and is fastened to a steel strip H, which keeps the whole system under definite tension and takes up the slack when the wire expands.

All this is mounted upon, but insulated from, a nearly semicircular metal plate, which has the same expansion coefficient as the hot wire itself, and thus eliminates the effect of changes of temperature in the surroundings.

The magnification depends on the fact that the movement of B due to sag is much greater than the actual extension of AC, when that extension is small. There are two such magnifications, at B and at the point of attachment of the silk respectively, and the result is a sufficient motion of the pointer without the use of gearing and with quite a small length of active wire. As usual, a non-inductive resistance is placed in series in the case of a voltmeter. For ammeters the wire is rather thicker, and instead of sending the working current through it from A to C, it may be led in at intermediate points and taken out at the ends or elsewhere, so that there are two or four paths through it in parallel.

As much as 4 amperes may in this way be sent through the wire, the remainder being carried by a shunt.

On the spindle carrying the pointer is fixed a light frame F cut out of thin sheet aluminium which, as the spindle rotates, moves in a very narrow gap between the poles of the steel magnet G. This acts in the ordinary way as a damping device, but in any case these instruments are naturally very dead-beat.

They also possess the great advantage of being equally correct on direct or alternating circuits, under all conditions and frequencies met with in practice, and are quite unaffected by external magnetic fields.

As the heating effect is proportional to the square of the current in wire, or the square of the P.D. across it, the scale will not be uniform, the divisions being crowded together at first and gradually getting further apart as the reading increases. Although this means the lower readings are not very reliable, it has the compensating advantage of giving a

bold and open scale at the part mostly in use. For instance, a voltmeter reading up to 240 volts would have an excellent scale from about 80 to 240. Below 80 the readings would be less reliable, and below 40 would be unreadable, that portion of the scale being left uncalibrated.

The most troublesome failing of hot-wire instruments is their tendency to burn out with moderate and even momentary overloads. They should always be protected with suitable fuses when in use. Sometimes even this does not save them when through some accident the over-load is large, for the time factor of the fuse comes in and it depends on which goes first, the fuse or the hot wire.

Another disadvantage is the fact that from the nature of the case the working current cannot be made as small as in the moving coil or certain other types, and, as a consequence, the ideal conditions as to resistance cannot be so closely approached. Voltmeters take about 0·2 amperes to give full deflection, and the P.D. across ammeters is about 0·4 volts under 100 amperes, and about 0·2 volts above 100 amperes.

INSTRUMENTS WITH SOFT IRON MOVING PARTS

This is a class of very useful instruments, based upon the mechanical forces acting upon soft iron when placed in a magnetic field produced by the current to be measured.

The details of the movement may vary considerably, but in all cases there is a small circular fixed coil. For ammeters this will consist of a few turns of suitably thick copper wire or strip (no shunt being required as in the previous instruments), and for voltmeters it will have sufficient turns to give the necessary field, and will be connected in series with a large non-inductive resistance placed inside the cover. In some instruments the moving part is simply a thin strip of soft iron pivoted inside the coil but out of centre, so that as it rotates it approaches the sides of the coil. Here the cause of motion depends upon the tendency of the iron to move into the strongest part of the field, which in the case of a short hollow coil is near the sides.

In others the deflecting couple is obtained by means of a fixed piece of soft iron inside the same coil, so that the two pieces of iron become magnetised similarly and repel each

other. Very frequently a "gravity control" is alone used, the same spindle carrying the pointer and a counterpoising weight, which is raised by the motion of the system. It is always desirable to reduce the actual amount of iron used as much as possible, and this is of especial importance for alternating current instruments.

The pattern introduced by Messrs. Kramer and Co. is shown in Figure 234. The coil, which is about 1 inch inside diameter and $1\frac{1}{4}$ inches deep, is wound on a brass bobbin B. The movement consists of a rotating soft iron strip A pivoted at the centre of coil as shown, the same spindle also carrying a pointer P and a small counterpoise C. This latter is merely for adjustment, the real control being a watch spring W, one end of which is fixed to the pointer and the other to a part of the frame (not shown in the figure). At the side of the coil is fixed a soft iron projection I which is very near to A, when the latter is in its zero position, actual contact being prevented by a brass stud fixed to I, and of such a length that A comes in contact with it if the pointer is moved slightly behind the zero position. When a current passes round the coil, I and A become magnetised similarly and repel each other. Thus A is rotated, but as the deflecting force decreases very rapidly with distance the range of motion would be small and the scale divisions very uneven were it not for the thin soft iron strip S, which is an extension of I round the inside of the coil as shown. This strip gradually becomes narrower from I to the end, and as a result the field near it gradually increases in strength, and there is a fairly uniform deflecting force through a considerable range of motion due to the tendency of A to set itself so that as many lines of flux as possible shall pass through it (see page 11). Thus the scale is opened out and the divisions made more nearly equal.

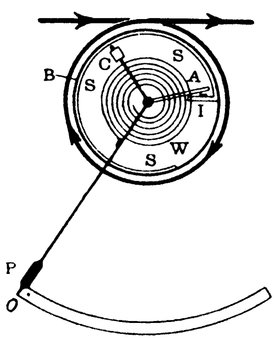


FIG. 234.

Generally speaking, instruments of this type possess many good points, and hence are largely used commercially. They

are inexpensive, will stand rough usage, and will work with either direct or alternating currents if suitably designed, and if properly made seldom require recalibration.

In recent years much improved instruments of this type have been produced, and dead-beat movements, with knife-edge pointers working over scales provided with mirrors to avoid parallax, are now readily obtainable.

ELECTROSTATIC INSTRUMENTS

The oldest electrostatic instrument is the familiar gold-leaf electroscope, and the principle is exactly the same in the most modern forms. In fact, an ordinary electroscope with one fixed and one movable leaf makes an excellent voltmeter for certain purposes, its most useful working range being from 200 to 600 volts ; and it has the advantage of being equally suitable for continuous or alternating currents.

The action of all electrostatic instruments depends upon the existence and properties of " lines of electric force." In this book it has been necessary and sufficient to concentrate our attention on the properties of lines of magnetic flux, but students who supplement their practical lessons with a theoretical course, as all should do, either know or will know that this is only one aspect of the subject, and that in all current phenomena the two distinct kinds of lines exist together and are equally important.

It must be sufficient here to remark that when we say a P.D. exists between any two points, it is only a particular way of saying that lines of electric force extend from one to the other through some intervening or surrounding non-conductor. As these lines tend to contract in length just as magnetic lines do (although they are very different in other respects), there must be a mechanical attraction or pull between any two bodies as soon as we produce a difference of potential between them, which, other things being the same, is proportional to the square of that difference of potential. Another but less satisfactory way of stating the same thing is to say that the two bodies become charged positively and negatively respectively and that these charges attract each other.

The practical difficulty in applying these facts is due to the

extreme smallness of the force in the case of moderate voltages and hence commercial instruments are mainly voltmeters for 1000 volts and upwards. For lower voltages excellent laboratory instruments are available, but they are almost too delicate for general use.

As an instance of the former kind we may take Ayrton and

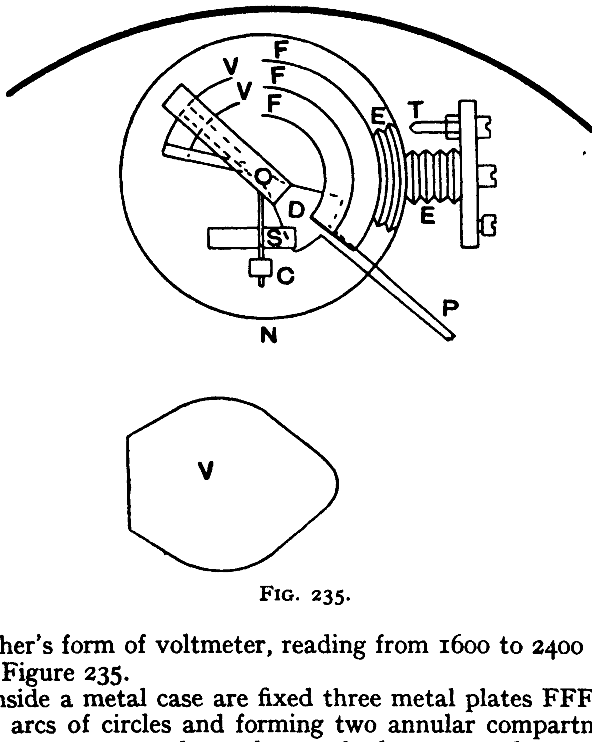


FIG. 235.

Mather's form of voltmeter, reading from 1600 to 2400 volts. See Figure 235.

Inside a metal case are fixed three metal plates FFF bent into arcs of circles and forming two annular compartments. These are connected together at the bottom, and are carried by an ebonite support E, which insulates them from the case. To the shaft carrying a pointer P and counterpoise C is attached a pair of light bent vanes VV which fit in between the fixed plates F, but without making contact anywhere. Their shape (flattened out) is shown below on a larger scale. These vanes are electrically connected to the case N by a fine

flexible wire. One terminal of the instrument goes to N, and the other to the fixed vanes F; when a P.D. is set up between them, one set of vanes becomes charged positively and the other negatively, i.e. lines of electric force pass from V to F, which tend to pull the two as closely together as possible until a position is reached in which the couple due to this pull is balanced by the opposite couple, due to the counterpoise. D is a damping device of the usual kind. It is a strip of metal attached to the system and moving between the poles of the steel magnet S. T is a screw in connection with the fixed vanes, and adjusted so that the distance between it and the case is less than the shortest distance between the fixed and movable vanes. It thus acts as a safety valve, for if the P.D. increased beyond a safe limit sparking would occur here first and do less damage, and the arc formed would immediately blow the fuses provided in the base of the instrument. The outer case is only indicated in the diagram.

Most electrostatic instruments have some such arrangement of fixed and movable vanes, and the sensitiveness can be increased by increasing their number. They are ideal in possessing infinite resistance and taking no power, and in being equally correct on all kinds of circuits and at all frequencies. On the other hand, the full working P.D. exists between closely adjacent conductors, and precautions must be taken against accidental short circuits.

Obviously the electrostatic principle is only directly applicable to voltmeters, but theoretically it might be used for ammeters by providing the movement with a suitable shunt, so that the latter really measured the P.D. across the shunt. Addenbrooke has worked out practically a complete scheme of measurement on this basis, and it has many advantages, but the moving forces available are so very small that it is difficult to turn the possibility to account except for laboratory purposes.

INSTRUMENTS OF THE DYNAMOMETER TYPE

If a current is passed through a fixed coil a magnetic field, whose strength is proportional to the current, will be produced within it. If, in this field, another coil, pivoted and spring controlled and carrying the whole or a fixed proportion of the

same current, is placed, a deflecting force proportional to the square of the current will be obtained, thus giving a movement which is suitable for use on either D.C. or A.C. circuits. The general arrangement of the movement (though not the relative connections of the coils) is similar to that shown for a dynamometer wattmeter in Figure 238. For use as a voltmeter the two coils each carry the full current, different ranges being obtained by the use of different amounts of series resistance. For use as an ammeter for low currents, the full current may also be passed through both coils, but, for larger currents, while the full current may still be passed through the fixed coil, the moving coil is usually connected across a shunt inserted in the main circuit. This obviates the necessity of carrying large currents to the moving coil which cannot be readily effected.

OHMMETERS

These are a very important class of instruments which indicate directly by their scale-reading the resistance of the portion of the circuit to which they are connected, and their especial sphere of usefulness is the measurement of insulation resistances such as are met with in power and lighting circuits, which are usually reckoned in megohms. Every wiring job must be tested for insulation before it is connected up to the mains; the method adopted must be extremely simple, and be capable of giving moderately accurate results.

The action of all true ohmmeters is based directly on Ohm's Law. We have already shown (see page 46) how to measure any resistance by putting an ammeter in series with it and a voltmeter across it, its value being then given by $R=\frac{V}{I}$. An ohmmeter is equivalent to the two instruments combined in one in such a way that the actual reading is proportional to the quantity $\frac{V}{I}$, which is constant whatever the applied voltage may be.

The first instruments of the kind were invented by Ayrton and Perry many years since. Of modern patterns, Evershed's ohmmeter is one of the best known.

In the 1904 pattern, shown diagrammatically in Figure 236, two galvanometer coils PP_1 and CC_1 are fixed at right angles,

the former being the voltage coil of high resistance and the latter the current coil of low resistance, and at their centre is a pivoted magnet N which carries a pointer. X is the unknown resistance to be measured, and G is the magneto-generator which is the source of E.M.F.

From what has been said above it follows that the current coil CC must be in series with X, and the voltage coil PP

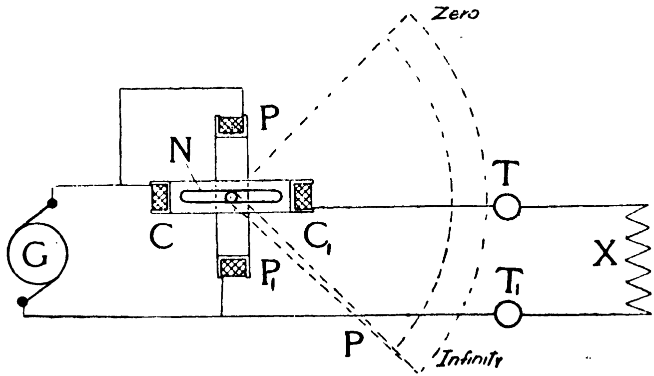


FIG. 236.

must be as a shunt across it. As shown, the latter is connected across both CC and X, which is practically the same thing. See arrangement in Figure 230, page 372.

First suppose X is infinite, i.e. an open circuit. Then there will be no current in CC when generator is turned, but a current will flow in PP proportional to the applied voltage. This will produce a field at the centre of the coil perpendicular to the plane PP, and whatever its previous position, the needle N will turn until it lies along this field, and its position will be the same whatever the voltage applied. The pointer P therefore now reads "infinity." If X have a resistance, however great, there will be some current in CC, which creates a new field at right angles to the other, and the needle will move until it points along the resultant field due to both. In other words, the effect of the current in PP is to produce a controlling force proportional to V, and that of the current in CC is to produce a deflecting force proportional to $\frac{V}{X}$.

In some position the moments of the couples due to the forces will balance, and the resulting deflection will be, roughly, proportional to $\frac{I}{X}$. Hence the scale can be calibrated directly in ohms or megohms, so that the largest deflection indicates the least resistance.

Although the result is independent of the applied voltage, and therefore of the rate at which the handle of the generator is turned, it is desirable to use always a high voltage (at least twice the working voltage) for testing purposes, in order to break down weak points. For this purpose a magneto generator is much more convenient than a battery, because it is portable and can be wound to give any voltage desired.

In the latest pattern, known as the "Megger," although the principle necessarily remains the same, the construction is entirely altered, and a much improved instrument is the

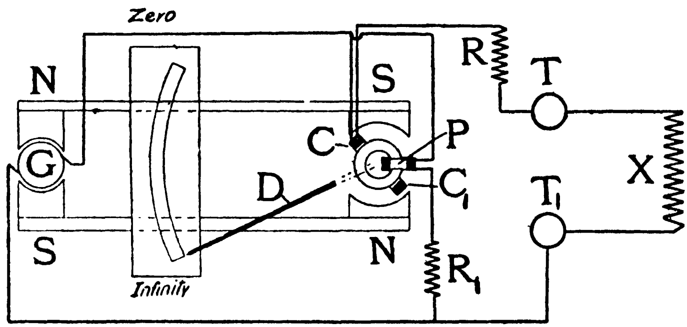


FIG. 237.

result. The working part is now of the "moving-coil" type, and the permanent magnet required is arranged so that it also provides the field for the generator, the whole being arranged in one case instead of having separate boxes for the generator and ohmmeter respectively (see Figure 237).

NS, NS are the steel magnets with their soft iron pole pieces, the generator G being at one end and the ohmmeter system at the other. This consists of a current coil CC_1, moving as usual in the gap between a fixed iron core and the polar face; and a voltage coil P arranged on the hollow core

itself, so that the only outer conductors are effective. These two coils are rigidly connected together and pivoted, so that they move freely whilst keeping the relative position shown, and the current is led in and out by very flexible fine wires which exert practically no control, so that when not in use the combination comes to rest in any position.

The circuit connections and the relative resistances must, of course, be the same as before.

In the coils themselves the direction is such that if a current were to flow through CC_1 alone, the coil would turn until it came to rest with C_1 in the position of D in the diagram, and if a current were to flow through P alone, the coil would move into the position shown and stop there.

Hence if the resistance X to be measured is infinite, so that no current flows through CC_1, on turning the handle the system moves into the position shown with the pointer indicating " infinity." If X have a resistance so that some current flows through CC_1, this will produce a clockwise torque of practically constant strength (as the field is uniform) and proportional to $\frac{V}{X}$; whereas the reverse torque on P, which comes into existence as soon as P moves, gradually increases as P gets into a stronger part of the field. This torque is proportional to V and to the angle of rotation, and when the system has turned until the two opposing torques are equal, the result will be a deflection roughly proportional to $\frac{I}{X}$.

This pattern is much more sensitive than the former, and may be constructed to read up to 2000 megohms. It is practically unaffected by external magnetic fields, and since the generator is mounted on the same base, the vibration from it eliminates any sticking due to friction at the pivots, and hence these can be made with large bearing surfaces (they are spherical and as large as a pin-head) not liable to be easily damaged.

All that is necessary in taking a reading is to place the instrument on a level base, connect up to the circuit to be tested, turn the handle a few times, and read off the new position of the pointer.

WATTMETERS

We have seen that the equivalents of an ammeter and voltmeter may be combined in one instrument to form an ohmmeter. In this case the two coils or parts work in opposition, one producing a "control" tending to resist deflection, the other thus being made to measure the ratio $\frac{V}{I}$, which is the resistance of the external circuit.

It would, however, be possible to make the component parts act together (providing an independent control due to a spring, or to gravity, etc.) and the resulting deflection would then depend upon the product VI, i.e. it would be a measure of the power expended in that part of the circuit to which the instrument was connected. The construction adopted in the ohmmeter already described is not very convenient or desirable for the present purpose, but this can readily be modified to suit the new requirements.

Wattmeters have hitherto been mostly of the "dynamometer" type, i.e. the moving force is due to the attraction and repulsion of currents in neighbouring coils of wire, as a rule no iron being used. There is a current coil, usually fixed, which consists of one or more turns of wire capable of carrying a suitable current; and a pivoted or suspended voltage coil of fine wire with a moderate number of turns (the fewer the better) which is in series with a large non-inductive resistance, often mounted on a separate stand.

Figure 238 shows a modern form of direct reading wattmeter.

B is the current coil, and F the movable voltage coil, which is in series with a non-inductive resistance not shown in the figure. The latter coil is pivoted on jewelled centres, one of which is contained in the cap C, and the current is conveyed in and out by two springs at H and L, which also serve as a control. A portion of the pointer is seen at K, the scale itself not being shown in the figure. A is a disc on which a brake can be made to rest, and which can be used for rapidly bringing the pointer to rest.

To measure the power being supplied to any given load or part of a circuit, it is connected up as in Figure 239.

Here MM are the mains or source supplying power to the load L. A is the current coil, V the voltage coil, and N the non-inductive resistance. If power is flowing to the circuit L, there will be currents in each of the coils and a deflecting force will be produced tending to turn the pivoted coil. The initial position of this coil is usually at about 45° to the fixed

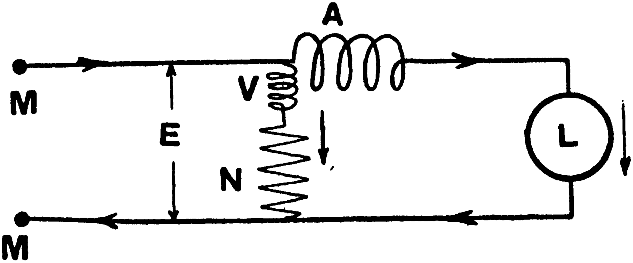


FIG. 239.

coil and the deflecting force will be arranged to tend to bring the two coils parallel to each other with the currents flowing in the same direction in each, the total range of movement being commonly about 90°. The deflecting force will be resisted by the controlling force of the spring and a deflection will be produced of such a value as will make the two forces equal to each other. To go into the matter more closely let, at any instant,

v=the voltage of supply,
i=the current through A and L,
i_1=the current through V and N,
R=the resistance of the path VN.

Then the deflecting force will, for one position of the moving coil, be proportional to $i \times i_1$ and since $i_1 = \frac{v}{R}$, this will also be proportional to $i \times v$. On D.C. circuits, so long as the load is steady, i and v will be steady, and, since with spring control the controlling force is proportional to the angle of deflection, we shall get a steady deflection which is proportional to $i \times v$ (for steady currents this may also be written $I \times V$), that is to the power being transmitted to the load.

On A.C. circuits the product of i and v will vary over wide

limits during a cycle, but the average deflecting force will be proportional to the average value of $i \times v$ (which is what we ordinarily understand as the power in an A.C. circuit, see page 241). The pointer will not follow the fluctuations of deflecting force during the cycle on account of its inertia, but will take up a position such that the average deflecting force is balanced by the control force thus indicating the average power during the cycle. In other words, the wattmeter will, on A.C. circuits, not only take into account the current and voltage but the power factor and will indicate $I \times V \times$ power factor (see page 244). Wattmeters are therefore of great importance in A.C. circuits where the simple product of current and voltage can never be relied on to give the true power.

SUPPLY METERS

These are automatically integrating instruments which measure either the ampere-hours, or the watt-hours, supplied to a circuit during some period of time. They form a large and highly specialised subject in themselves, and we can only briefly mention them in this chapter.

We shall take the well-known Thomson instrument (made by the British Thomson-Houston Co., of Rugby, to whom we are indebted for the diagrams) as an instance of a watt-hour, or true energy meter. It is really a two-pole motor with drum armature, but without iron. Figure 240 shows the general appearance of a pattern for medium loads, and Figure 241 shows the scheme of connections.

FF are two fixed rectangular field coils which are in series with the load, and carry the whole current supplied to it. These produce a horizontal magnetic field in which rotates a drum-wound armature A, consisting of eight coils of fine wire supported on a light non-magnetic frame, and mounted on a vertical axis fitted with jewelled bearings. This is in series with a large non-inductive resistance R, carried inside the case, and also with two starting coils SS, which are really auxiliary field coils placed inside FF, and producing the same polarity. This combination of armature, resistance, and coils is connected up like a voltmeter coil as a shunt to the load, and is always carrying a current, whether there is any load or not. The small eight-part commutator C with

segments of silver is below, and on it press delicate brushes of silver strip attached to phosphor-bronze wires. Above the armature a copper disc D is fixed to the axis, rotating with it between the poles of two steel magnets NS, NS. This arrangement can be seen in Figure 240; in Figure 241 the magnets

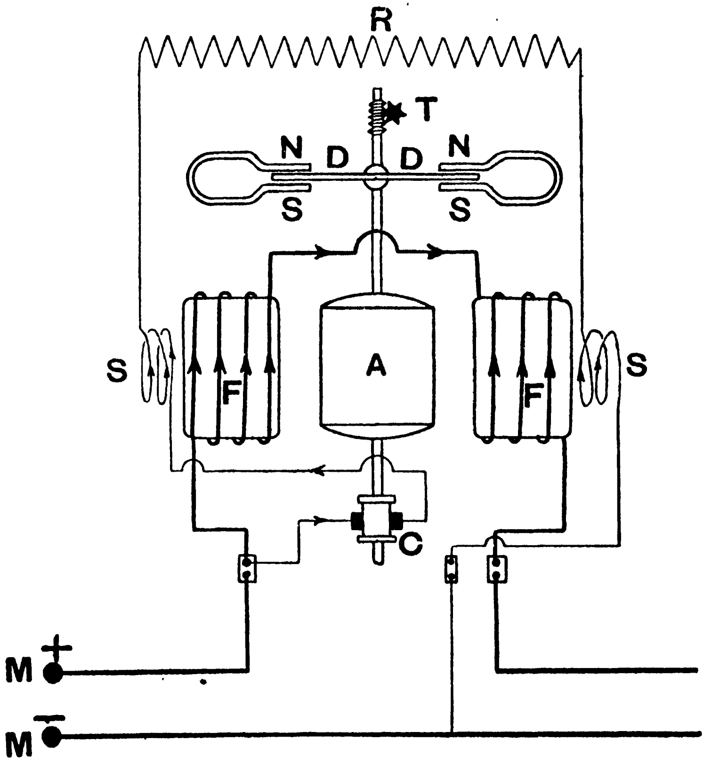


FIG. 241.

are drawn out of their natural position for the sake of clearness. At the top the axis gears into a train of wheels which register the number of revolutions; this train of wheels is fitted with a dial plate, which is usually graduated to read in Board of Trade units direct.

The principle is as follows: In the first place the record

must take into account not merely the watts supplied to the load but also the time for which they are supplied, and it must do this for loads which are continually varying.

For the sake of illustration, suppose that with a load of 500 watts the armature makes 1 revolution in 1 second (taking numbers merely for simplicity). Then if this load remains constant for two hours, the energy supplied to the system will be 1000 watt-hours, or 1 B.O.T. unit, and in this time the wheel-work will have registered 7200 revolutions. If the load is constant for 4 hours, 2 B.O.T. units will have been supplied and twice that number of revolutions recorded, and thus the scale must be marked so that every 7200 revolutions of the axis indicate 1 B.O.T. unit.

Again, if the load is doubled, 1 B.O.T. unit will be supplied in one hour instead of in two, and for this to be correctly recorded the speed must be twice as great.

We are thus led to see the conditions a motor meter must satisfy. It must run at a definite and constant speed on a constant load, and when the load varies the speed must vary with it, i.e. if the watts are doubled the number of revolutions per second must be doubled, and so on. Then it will indicate correctly the total B.O.T. units supplied in a given time even when the load is very variable.

We have now to see how these conditions are realised in the present instrument. As no iron is present the coils FF produce a field which is directly proportional to the current supplied to the load, and the armature is always carrying another current which is directly proportional to the supply voltage. But the force on a conductor carrying current in a magnetic field depends only on the strength of the field and the strength of the current, and therefore a driving torque is produced which is directly proportioned to the watts IV supplied to the circuit. Hence the armature begins to rotate, and if it were merely freely pivoted with negligible friction it would steadily increase in speed whatever the value of VI, until its back E.M.F. as a motor became practically equal to applied E.M.F.

Evidently something is required equivalent to the control of a deflectional instrument, and in the present case this is provided by the copper disc D, which, as it rotates in the field due to the steel magnets, produces a retarding torque

which increases directly as the speed. (For the E.M.F. induced in the disc is proportional to the speed, and therefore the induced current also, as the resistance of the disc is constant. Finally, the retarding torque depends on the strength of the field, which is constant, and the strength of the induced current, and hence varies as the speed.)

Therefore, as the speed of the armature increases so also does the retarding torque, until the latter becomes equal to the driving torque. Then the speed remains constant as long as the product VI is constant, and varies with it as required by theory.

So far we have assumed the bearings to be frictionless. This cannot be quite true, and, as a consequence, a small load might be supplied without the motor starting at all, for the current in the field coils would have to reach some small but definite value before the driving torque became sufficient to overcome the friction. The two starting coils SS are intended to compensate for this as far as possible. As the armature portion of the circuit is always across the mains at a constant voltage there is always the full current in it and always a weak field, due to the coils SS, tending to start it, and by using a suitable number of turns the torque due to this field can be made nearly but not quite enough to balance the starting friction, so that a very small additional load current sets the armature in motion.

This form of meter not only reads correctly when the supply voltage is liable to variation, but also on alternating circuits. (This statement must be understood to mean correct within reasonable working limits, for in consequence of many little difficulties and sources of error which we are unable to discuss in detail, no motor meter reads absolutely accurately at all loads.) It is well adapted for switch boards and large plants, but is rather too expensive for small-house installations.

In fixing it care must be taken that it is free from vibration, otherwise the slight jarring and consequent sparking will in time cause blackening of the commutator and introduce imperfect contact which will make the readings too low.

AMPERE-HOUR OR COULOMB METER

For many purposes it is not really necessary to take into account the voltage of supply as well as the current. If the

voltage is constant, as it always is in practice within a very small percentage, an ampere-hour meter will be equally satisfactory and can be made to read in B.O.T. units at any given voltage.

A "coulomb" is an ampere-second, and the term "coulomb meter" conveniently distinguishes between an instrument which only measures "quantity" and one which, like that just described, really measures the energy and is a "watt-hour meter," although the scale in either case may read in kilowatt-hours as a matter of fact.

Such an instrument is naturally less expensive to make because it requires only one circuit instead of two, and further, when in use there is no energy continually being wasted in a shunt circuit whether there is any load or not. For small-house installations using only a few lamps it is especially necessary to use a simple and inexpensive type of meter, and as an example we may take the "O.K." pattern, also made by the British Thomson-Houston Co. This is for direct currents only, and is made in sizes to carry from 1 to 15 amperes. It is essentially similar in principle to the instrument just described, but the field is produced by a steel permanent magnet, and there is no electromagnetic or other control.

It is shown in Figure 242. The magnet is of the horseshoe type with poles made slightly concave to take the armature. This is similar in construction to that already described and, like it, rotates on a vertical axis fitted with a commutator below; but in this case there are four coils wound on a hollow frame, within which is a fixed core of soft iron to concentrate the field.

The load current passes through a wire of "constantan" (seen in a vertical position on the right), and the armature is arranged as a shunt to this wire. The resistance of the constantan is such that there is half a volt P.D. across it at full load, whatever the capacity of the meter, and thus the same armature construction serves for all sizes, its resistance being such that half a volt will send from $\frac{1}{1000}$ to $\frac{2}{1000}$ ampere through it. This is a smaller working current than could be used in the previous instrument because the field is now so much stronger, and hence a smaller commutator can be used, whilst to avoid corrosion the segments and brushes are made of gold.

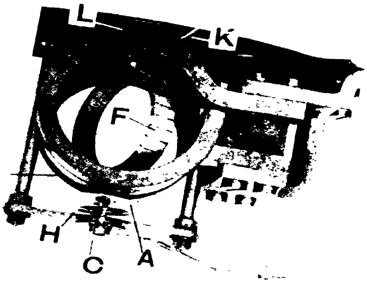


FIG. 238

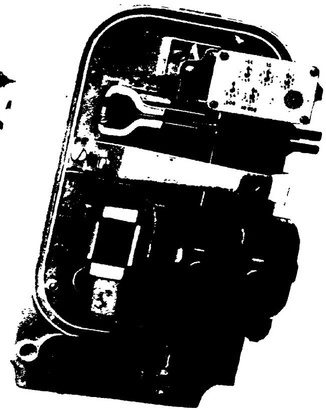


FIG. 240

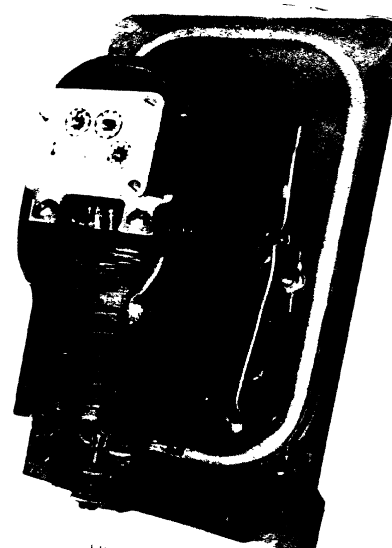


FIG. 242

As the field is constant the driving torque will depend only upon the armature current, and this is directly proportional to the load current; but as on this meter there is no control, the armature accelerates until its speed is such that the back E.M.F. nearly equals the P.D. of half a volt or less (according to the load), which is applied to the brushes. The energy taken, then, just balances the heat and friction losses and is very small. It is possible to dispense with a control in this case because, on account of the strong field and the small applied voltage, the necessary back E.M.F. is produced at a speed which, although higher than usual in meters, is not unreasonably large. (With the previous instrument under similar conditions the speed would become excessive before a steady state was reached, and hence the advantage of a larger controlling load.)

The direction of running will depend on the direction of the current in the armature, and therefore the instrument cannot be used on alternating circuits. For this latter purpose a special class of inexpensive and compact instruments is now largely made, which work on the principles embodied in induction motors, and are not explained in this book.

It is only with alternating currents that the distinction between ampere-hour and watt-hour meters becomes of much importance to the householder. For instance, he may run one arc lamp taking, say, 10 amperes at 45 volts in series with a choking coil on 100-volt mains, and congratulate himself upon the fact that the choking coil wastes but little power. But if he is supplied through a coulomb meter it will read just as much as if he took 10 amperes at 100 volts, and the real saving will be to the supply company, whereas an energy meter would take the circumstances into account and read accordingly.

RESISTANCE AND ITS MEASUREMENT

The simple voltmeter and ammeter method, sufficiently correct for many purposes, has already been mentioned. More exact determinations are in practice always made by comparison with standard resistances of known value, because it happens to be very easy to make such comparisons with great accuracy, and very difficult to determine the actual

value of any given resistance without such a standard. In fact, we might say that practically the whole system of electrical measurements is based upon the possession of a standard 1-ohm coil and a standard cell.

The most generally useful method of comparison is by means of a Wheatstone's Bridge. The principle of this method is very easily understood.

Suppose a stream of water is flowing down a hillside, dividing at A into two branches which reunite again at some lower level B (Figure 243). It is at once obvious that if we fix upon any point in one branch, say D, then there must be somewhere a point in the other branch which is on the same level, say F, and this must be true no matter how widely the branches may diverge, or how they may differ in length or carrying capacity. Further, it would theoretically be possible to find the second point experimentally, for if a channel be cut or a pipe connected from D to the other branch, there would be no flow through it if it made connection at the right point F, and there would be a flow in one direction or the other if it made connection anywhere else.

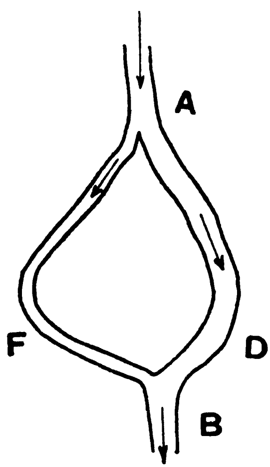


FIG. 243.

These conditions are essentially similar to those in an electric circuit, only to our senses an electrical P.D. is not so readily perceptible as a gravitational difference of level.

For let Figure 244 represent two conductors in parallel so that the total current divides up into two paths. Then there is a definite fall of electrical level between A and B which we call the P.D. between them, and if we take any point D in one branch there must be some point F in the other at which the potential is the same, that is, such that the P.D. between A and D is equal to the P.D. between A and F. Of course it equally follows that the P.D. between D and B is equal to the P.D. between F and B. This point F can be found by

connecting a galvanometer to the first point D and exploring the second branch with a movable contact. There will be a deflection in one direction or the other unless contact is made exactly at F, and by using a sensitive galvanometer this point

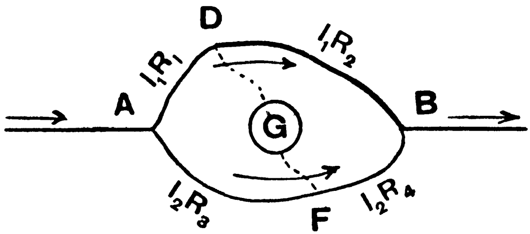


FIG. 244.

can be fixed with great precision. The usefulness of these operations depends upon the fact that when this condition of balance is obtained there is a simple relation between the resistances of the paths AD, DB, AF, and FB, which constitute the four arms of the "bridge." Let these be R_1, R_2, R_3, R_4 respectively, and let the total current divide up into two parts, I_1 and I_2 (as there is NO current through DF).

Then P.D. between A and D $=I_1 R_1$,
,, P.D. ,, A and F $=I_2 R_3$.

But we have shown these are equal,

$$\therefore I_1 R_1=I_2 R_3 \ (1).$$

Again P.D. between D and B $=I_1 R_2$,
and P.D. ,, F and B $=I_2 R_4$

$$\therefore I_1 R_2=I_2 R_4 \ (2).$$

Hence dividing (1) by (2)—

$$\frac{R_1}{R_2}=\frac{R_3}{R_4}$$

Which may also be written—

$$\frac{R_1}{R_3}=\frac{R_2}{R_4}.$$

This shows that if one of the resistances be actually known and also the ratio of two others, the fourth can be calculated.

The principle itself can be used practically in quite a number of different ways. Here it will be sufficient to outline two of the best known.

The first or "slide-wire" bridge is of more use in the laboratory than to the practical man. Referring to Figure 245, the arms AD and DB become gaps in which the known and the unknown resistances can be placed, and AFB becomes a uniform wire of some high resistance alloy, usually either 1 metre or ½ metre in length and provided with a scale of

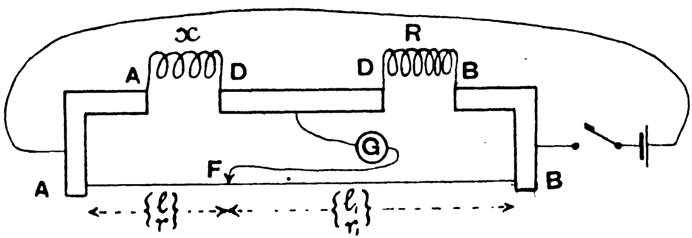


FIG. 245.

equal parts, the necessary connections being made by massive metal lugs of usually negligible resistance.

Figure 245 shows the arrangement lettered to correspond to the first diagram. Evidently if x and R are the unknown and known resistances respectively, and F the point of contact giving balance, we have by the previous result

$$\frac{x}{\mathrm{R}}=\frac{\text{Res. of AF}}{\text{Res. of BF}}$$

but this ratio is, in the case of a uniform wire, the same as the ratio of the lengths, and therefore

$$\frac{x}{\mathrm{R}}=\frac{l}{l_1}$$

where l and l_1 are measured on any convenient scale (usually millimetres).

As the method of working and precautions required are given in every theoretical textbook, it is needless to discuss these matters here, except to remark that although apparently the possession of a single known resistance is all that is

required to evaluate any other, practically accuracy can only be obtained when x and R do not differ widely in order of magnitude.

Hence, as a rule, a range of known resistances is required, and these are conveniently made up in the form of a "Resistance Box," whose construction is shown in Figure 246.

The coils themselves are made of some high resistance alloy

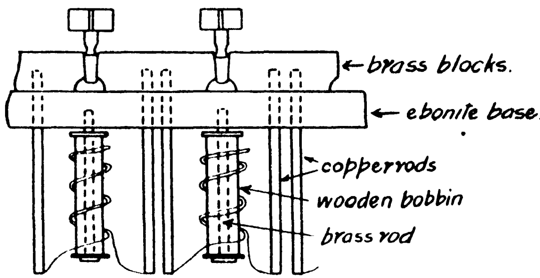


FIG. 246.

with a low temperature coefficient, such as platinoid, manganin, etc., and wound, so as to be as non-inductive as possible, on little wooden bobbins and slipped over brass pins screwed into the lower surface of a sheet of ebonite. On the upper surface is a series of brass blocks with gaps between fitted with brass plugs, and the ends of the coils are soldered to thick copper rods screwed into these blocks.

When the plug is in, the coil is short circuited by a usually negligible resistance, and by taking it out the coil is thrown into the circuit. The resistances of the coils are so arranged that any integral number of ohms from unity up to the maximum can be made up with the smallest possible number of coils, and one of the plugs, marked "Infinity," has no coil attached to it, and thus serves as a convenient key for opening and closing the circuit.

The second method, most generally useful for moderately exact measurements throughout a wide range, omitting both extremely high and extremely low resistances, is exemplified by the particular arrangement long known as the "Post Office Pattern of Wheatstone's Bridge," or "Post-office Box."

Its special advantages are compactness, portability, and convenience in use. It is easily understood by comparing it with the simple theoretical diagram.

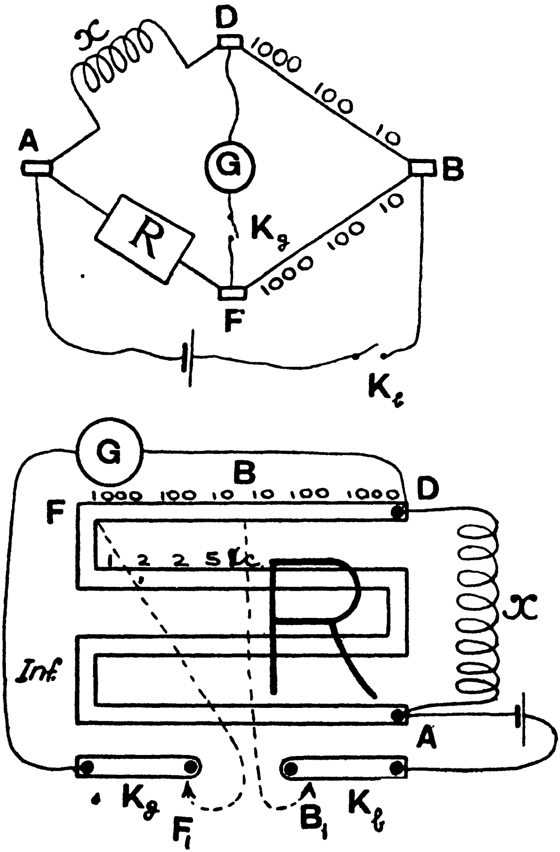


FIG. 247.

Let A, D, B, and F, Figure 247, be merely four massive brass terminals, to which the galvanometer and battery are permanently connected as shown and provided with contact keys.

Let the unknown resistance x be connected between A and D, and a resistance box between A and F.

In the other two arms DB and BF are placed the proportional coils, usually 1000, 100, and 10 ohms respectively, any or all of which can be used.

Evidently if the resistance in BD is made equal to that in BF, balance will be obtained when R is equal to x.

The actual arrangement is shown in the figure, where the coils are understood to be fitted underneath brass blocks as already described. Here FF_1, BB_1 are permanent connections inside the box to metal studs at F_1 and B_1, and K_g and K_b are tapping keys which when depressed close the galvanometer and battery circuits respectively as required by the upper diagram. Before making any measurement it is necessary to see that all plugs make a good contact, by giving each one a slight screwing twist. Then take out the plugs of two proportional coils of equal value. Apparently there is no reason to choose, say, two 10-ohm coils in preference to two 100-ohm coils, or two 1000-ohm coils, but theory shows that it is best to use the pair of coils nearest in value to the resistance to be measured. Of course it may be necessary to make a preliminary measurement to find out the approximate value of x.

It is convenient to determine at once the direction of deflection of galvanometer needle for R "too little" and R "too much."

This can be done by closing the battery key, then *momentarily* depressing the galvanometer key, so as not to injure the galvanometer. Note the direction of the deflection and then take out a plug of rather high value and repeat until a deflection in the opposite direction is obtained. This fixes the superior limit to the value of x, and the plugs can be altered until the addition of one ohm reverses the direction of deflection.

Note that the battery key must always be depressed first; for if the galvanometer key is first closed, a "throw" will be obtained in any case if x is inductive, whether the balance is correct or not.

This throw is momentary, whereas the deflection due to want of balance remains steady as long as the key is depressed.

In this way the value of x is determined to the nearest

ohm, provided that it is not greater than the total available value of R. This range can be extended by using proportional coils of different value. Suppose in a given case x is found to be between 67 and 68 ohms, then if the 10 and 100 ohm coils are unplugged, as at A in Figure 248, we see the condition of balance is that $x = \frac{1}{10}$ R.

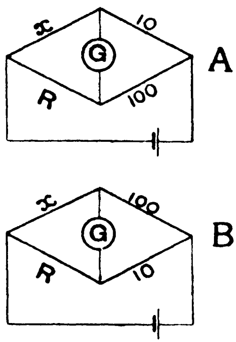


FIG. 248.

On trial balance may now be obtained between 674 and 675 ohms, which means that x is between 67·4 and 67·5 ohms, and thus the first decimal is determined.

If the arrangement as at B is adopted, balance will be obtained when $x = 10$ R, and thus resistances up to ten times the full available known resistance may be evaluated. Similarly 10 and 1000 may be used with a still more extended range, assuming these ratios to be exact. But as absolute exactness is in practice impossible, results found in this way must be regarded as close approximations, quickly and easily obtained.

THE POTENTIOMETER

To conclude the chapter on measurements it is desirable to consider briefly the mode of action of the potentiometer which is of first-class importance in connection with the comparison of voltages and also, indirectly, of currents and resistances. Consider a battery of accumulators B sending current down a uniform conductor AD. The voltage drop between two points on this wire as A and E will be proportional to the length of wire AE (since the resistance is proportional to the length and the current is the same at all parts of the wire). If we connect another circuit ACE, containing a cell C (having a smaller E.M.F. than that of the main battery) and a galvanometer to the first circuit as indicated in Figure 249, then, if the polarities are as shown, it will be possible to select a point E on the wire AD such that the fall of potential down the wire AE is equal to the E.M.F. of the cell C. The two voltages will oppose each other in the circuit AGCE

and there will be no deflection of the pointer of the galvanometer. If contact is made at any other point of the wire, as E_1 or E_2, there will be a deflection of the galvanometer one way or the other depending upon whether the fall of potential

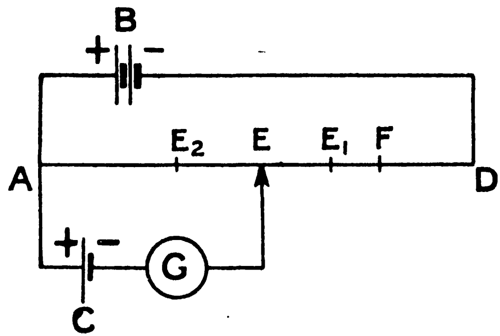


FIG. 249.

down the wire is greater (as at E_1) or less (as at E_2) than the E.M.F. of the cell C. If the cell C is replaced by another cell (or other source of E.M.F.) and a balance again obtained with a length of wire AF, we then have

$$\frac{\text{E.M.F. of cell C}}{\text{E.M.F. in second case}} = \frac{AE}{AF}.$$

If the cell C is a standard Cadmium cell of known E.M.F., the E.M.F. in the second case can be readily calculated. Instruments working on this principle are termed potentiometers and, if carefully designed and constructed, permit of the comparison of voltages with considerable accuracy. In practice AD is not usually a single straight wire but may be divided into, say, 15 parts, the first 14 parts consisting of coils, contact on to which is made by a single pole multi-way switch, while the other part may consist of a straight wire on to which a sliding contact is made for the purpose of fine adjustment (see Figure 250). The potentiometer can be used to measure a current if this is passed through a known standard resistance and the resulting voltage drop measured. An unknown resistance can also be compared with a known resistance if the same current is passed through each and the

respective voltage drops compared. In practice it is usual to adjust the value of the current sent by the battery B through the potentiometer wire to such a value as will make the

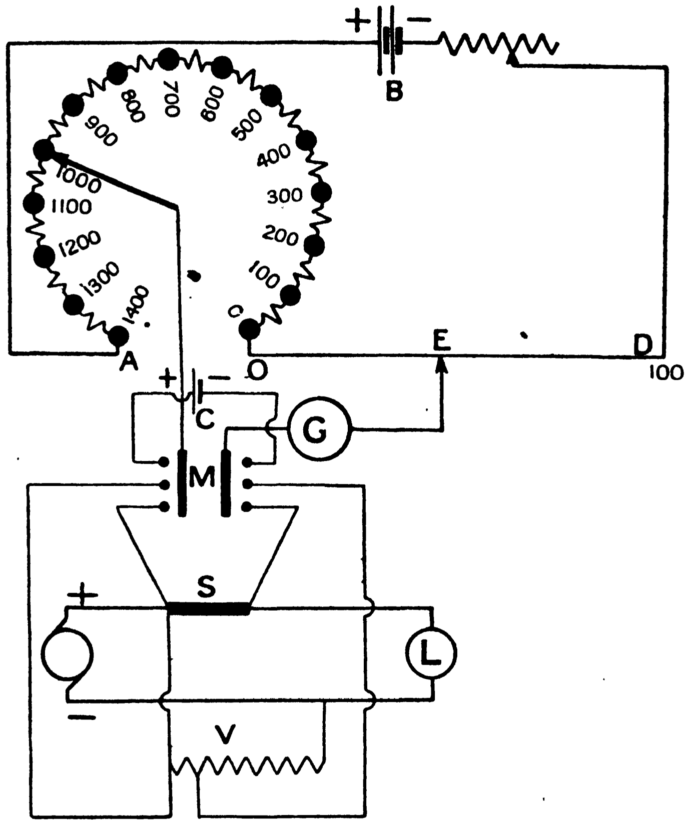


FIG. 250.

instrument direct reading. Thus, if there are 1500 divisions on the wire (1400 in coils controlled by the single pole multiway switch and 100 in the straight wire) the main current is adjusted so that the voltage of a Cadmium cell (1·02) is balanced when it is connected across 10 of the large divisions

and 20 of the small divisions on the wire, thus making each of the small divisions equal to 0·001 volt.

Figure 250 shows a potentiometer arranged to measure the current and voltage taken by a lamp L. To assist in rapid work the several voltages to be measured are taken to a double pole multi-way switch M, the standard cell for calibrating the potentiometer wire being connected to the top contacts. The bottom contacts of M are connected to the terminals of a standard known resistance connected in the lamp circuit, thus allowing for the measurement of the current. To measure the voltage on the lamp (which is too high for direct application to the potentiometer), a volt box V is connected across the mains and, say, $\frac{1}{200}$ of the voltage tapped off and connected to the middle contacts of M for measurement on the potentiometer.

CHAPTER XV

PRIMARY CELLS AND ACCUMULATORS

IN this chapter we break ground in a new direction, and the previous lessons will help us very little. It is not even possible to make an intelligible statement of the facts without assuming some elementary acquaintance with chemistry, the principles of electrolysis, and the construction of the simpler forms of primary cells. Such matters can be much better treated elsewhere, and we prefer merely to outline the subject in a way likely to be helpful and stimulating to students who have already obtained the slight amount of preliminary knowledge required.

A cell of any kind is a device for liberating and setting in motion the electric charges locked up in the molecule of some chemical compound. A primary cell is one in which the working substances are removed at intervals and replaced by new active material; a secondary cell or accumulator is one in which the chemical processes are reversed, and the working substances brought back to their original state by passing a current through the cell in the reverse direction for a sufficient time.

There is no fundamental difference between the two. The recharging property by the passage of a reversed current is a necessary consequence of the facts of electrolysis, and is therefore possessed more or less by all cells; but whereas an accumulator is designed to take full advantage of it, in the case of a primary cell such reversal is usually difficult or impossible for practical reasons, and it becomes very much more convenient to renew the plates and solutions when necessary.

Primary cells are useful and economical when small quantities of electrical energy are required at intervals. As

generators on a large scale there is apparently no future for them, the cost being prohibitive. It is easy to show that this is the case if zinc be used, for the laws of electrolysis tell us that a total quantity of 370 ampere-hours can be obtained by the consumption of 1 lb. of zinc whatever the solution used to dissolve it and whatever the time taken in the process. The voltage obtainable will depend on the constitution of the battery, but under actual circumstances it is not likely to exceed 2 volts, and will almost certainly be less. Hence assuming complete utilisation of the zinc and an improbably high voltage, and ignoring altogether the cost of the solution, plant, and maintenance, we get about 740 watt-hours for 1 lb. of zinc which might cost 3d. This means about 4d. for the cost of one Board of Trade unit, as against 1d. or less when produced by dynamos, and this figure cannot be reduced by any invention or improvement, unless some other metal be used or unless the price of zinc falls considerably, whilst as a matter of fact the total cost in practice works out to at least three or four times as much.

A cell usually contains (1) an exciting fluid, which must be an electrolytic conductor, (2) two plates or sets of plates which must be conductors, one being attacked by the exciting fluid and the other not, (3) a depolariser.

The exciting fluid is usually a solution of an acid, an alkali, or some simple salt in water, and this dissolved substance may be regarded as the source of the electric charges whose ordered flow constitutes a current. In a primary cell it is the function of the zinc plate to decompose this substance and thereby liberate its store of electric charges, for a current is generated by the breaking up of a compound, not by its formation, and it is misleading to regard the solution of the zinc as its source, although the latter supplies the energy given out by the cell, and largely determines the magnitude of the E.M.F.

If sulphuric acid be the active substance, we may regard each molecule of H_2SO_4 as carrying equal quantities of positive and negative electricity, each hydrogen atom possessing a certain positive charge of definite amount, and the SO_4 group twice as much negative to balance. The total quantity is easily calculated from electrolytic data. It is 245 ampere-hours for 1 lb. of pure sulphuric acid, and when the cell is at

work we can roughly visualise the processes involved by imagining the SO_4 groups to be giving up their negative charges to the zinc plate as they combine with it to form zinc sulphate, and these negative charges to be flowing round the external portion of the circuit until they reach the other plate; and there neutralising the positive charges on the hydrogen atoms in contact with it, which then appear as free gas. There is good reason to believe that only negative charges can thus flow round the circuit, and that it is not a question of the hydrogen giving up its positive charge to the plate, but the reverse, as stated above. There is, however, some very real difficulty about this last process; the transfer of charge from plate to hydrogen does not go on very readily, and thus is produced the effect known as "polarisation." If the hydrogen particle could combine chemically with the plate the transaction would be easy enough, but there is no substance with the necessary affinity for hydrogen. Practically the same result can be obtained by surrounding the plate with a depolariser, i.e. some substance which is in conducting contact with the plate and which has loosely held negatively charged atoms ready to combine with the hydrogen. The essential factor is the nature of the depolariser; that of the plate is immaterial, except that it must not be acted upon chemically by either the depolariser or the exciting fluid.

The only primary cells of practical importance are the Leclanché cell and its modification the so-called Dry Cell. In the former, and usually in the latter, the exciting fluid is a solution of ammonium chloride (NH_4Cl.); 1 lb of this salt contains 227 ampere-hours, and is, therefore, equivalent to 0·6 lb. of zinc. Its special merit is the small amount of "local action," i.e. very little wasteful consumption of zinc goes on when the cell is not in use. It is a mistake to suppose that such local action does not occur at all; as far as that goes, perfectly pure zinc would be equally free from it in either dilute sulphuric acid or ammonium chloride solution; but the presence of impurities in ordinary zinc causes voltaic action in both cases, in the manner described in any theoretical textbook, and hence the zinc should be amalgamated even in a Leclanché cell.

The arrangement of the zinc and carbon plates is largely a matter of convenience, as the cell is not intended to give

out any large output of current and "efficiency" is not so important as simplicity and low cost. (It is almost obvious that in all cells from which a large current is required the plates should be as large in area and as close together as possible consistent with the proper circulation of the exciting fluid.) The depolariser is manganese dioxide, not because it is especially effective, but because it has no troublesome chemical action on either liquid or plates, and, therefore, does not cause deterioration when the cell is left without attention for long periods of time. It is, in fact, rather slow in action, but the nature of this action is essentially the same in principle as that of the lead dioxide to be referred to below in connection with accumulators.

A sectional view of a dry cell is shown in Figure 251, in which the constructive details are sufficiently clear to make a detailed description unnecessary. The zinc plate now forms the containing vessel, and is itself enclosed in a cardboard case in order to facilitate insulation when the cells are grouped together in batteries. Packed around the carbon rod is a black paste forming the depolariser, made up for convenience in a loose bag of porous or perforated paper or sacking. This paste varies in composition, the following being a good mixture :—

50	parts	manganese dioxide
34	,,	powdered carbon
16	,,	graphite (black lead)

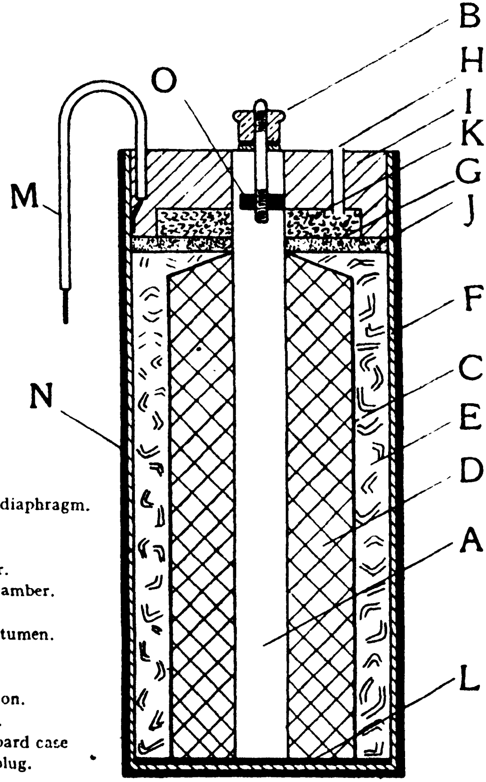
made into a paste with glycerine and ammonium chloride solution.

The black lead increases the conductivity and serves as a binding material. A larger proportion of manganese dioxide might be used, but as this is the most expensive item it is kept down as much as possible.

The white paste, corresponding to the exciting fluid, may have the following composition :—

12	parts	ammonium chloride
6	,,	zinc chloride
6	,,	glycerine
6	,,	flour
35	,,	plaster of Paris
35	,,	water.

Here the function of the flour and glycerine is to give stickiness and consistency and that of the plaster of Paris to take up water. The zinc chloride is added because it is deliquescent and for no other reason. This mixture is put into



A. Carbon rod.
B. Terminal.
C. Thin porous diaphragm.
D. Black paste.
E. White paste.
F. Zinc cylinder.
G. Collecting chamber.
H. Glass tube.
I. Sealing of bitumen.
J. Sand.
K. Sawdust.
L. Wax insulation.
M. Wire to zinc.
N. Outer cardboard case
O. Lead fixing plug.

FIG. 251.

the zinc vessel, and by means of a mould made into a layer around the sides, as shown in the figure. Then the mould is removed and the previously prepared bag containing the depolariser and the carbon rod is slipped in place of it. The thinner the layer of active material the smaller will be the internal resistance, and also the shorter the "life" of the cell.

Finally a layer of sand is placed above the paste, on this a layer of sawdust arranged as shown, a glass tube is inserted to permit escape of the gas formed during the action of the cell, and the whole sealed up with pitch or bitumen. As regards the former materials, if sawdust were to be used alone it would always be absorbing moisture out of the pastes, and if sand were used alone it would not be sufficiently absorbent to take up any surplus moisture which rises in the cell. The sawdust is therefore placed above the sand, and is able to take up any excessive moisture which may rise without encouraging that tendency.

In order to obtain the best results, certain precautions must be taken during manufacture. In the first place attention must be paid to the purity of the chemicals used, for any impurities will be certain to set up local action; and the inside surface of the zinc must be amalgamated for the same reason. Again, it is important that the top of the carbon rod should be thoroughly soaked into melted wax to avoid creeping and slow chemical action on the terminal. To ensure good contact between the carbon block and the brass terminal, melted lead may be run in through a hole in the side of the former, as shown in the figure.

Dry cells are now generally made circular in section and with circular carbon rods. This gives everywhere the same distance between the plates and tends towards uniform wear; with cells of square section the zinc is sure to be eaten away unequally at different places.

Since the advent of wireless reception a great demand has arisen for dry cells of small capacity for supplying current to the plate circuits of thermionic valves. In most cases the maximum current demand is of the order of 10 to 20 milliamperes and the cells are commonly supplied in cardboard boxes containing a sufficient number of cells connected in series to give a total voltage of 60 to 120. Sockets are connected at suitable points in the chain for the insertion of wander plugs.

REVERSIBILITY

When a Leclanché or dry cell has been working for some time, part of the zinc has become zinc chloride, some oxygen has been lost by the manganese dioxide, some water has been

formed, and some ammonia gas has escaped into the air or been absorbed by the liquid. If we now send a current the reverse way through the cell, it is true that some zinc may be redeposited on the zinc rod, but complete regeneration is impossible; for if that is to occur, it is in the first instance essential that no constituent of the active substances shall be lost during discharge, as the ammonia has been in this case.

Neither is it desirable that the active plate should dissolve in the solution, as does zinc, for if so it will certainly not be perfectly regularly redeposited during the charging process. Again, the depolariser must be as harmless and insoluble as the manganese dioxide and yet be chemically energetic in its behaviour and a good conductor, preferably forming an insoluble substance when deoxidised. Finally the plates must be free from local action and the combination should give a fairly high electro-motive force.

These somewhat stringent conditions are better satisfied by plates of lead and lead dioxide (PbO_2) in dilute sulphuric acid than by any other materials known at present. Many attempts have been made in other directions; in one or two instances with some success; but, on the whole, the lead cell holds its own without any prospect of being generally superseded.

Imagine a primary cell with plates of lead and of lead dioxide in dilute sulphuric acid. The only constructive difficulty is with the latter plate, for the material is not naturally a solid, coherent substance, and it may require special manufacture, or more conveniently the active substance may be supported as a coating on some suitable metal carrier. It is one of the few compound bodies which are also fairly good conductors, and to this, as well as to its qualities as a depolariser, it owes its value. The result is a very good cell with an E.M.F. of about 2 volts, the internal resistance, of course, depending mainly on the size of the plates and their distance apart. If the acid is not too strong there is no local action worth mentioning on open circuit. When the circuit is closed, chemical action occurs at both plates. At the lead plate (known as the negative plate, and corresponding to the zinc of an ordinary cell), the SO_4 groups form lead sulphate ($PbSO_4$), unloading at the same time their negative charges. As lead sulphate is insoluble it forms a thin surface layer,

and speedily stops the whole working of the cell by protecting the plate from the solution. At the dioxide plate, known as the positive plate, and corresponding to the carbon of an ordinary cell, positively charged hydrogen particles appear, to be neutralised by negative charges flowing round the circuit, always an easy process when chemical combination occurs. In the present instance the dioxide furnishes negatively-charged oxygen atoms which combine with the hydrogen to form water, and in consequence becomes itself positively charged and reduced to litharge (PbO). This substance is, however, attacked by the surrounding acid, and the reaction

$$PbO + H_2SO_4 = PbSO_4 + OH_2$$

occurs, water being formed, and another thin coating of insoluble sulphate formed upon this plate also, with a similar tendency to stop the action. Meanwhile the solution has been decreasing in density, for it has lost some SO_4 at both plates and gained water.

If now a current from some external source be sent through the cell in the reverse direction, the acid solution will be electrolysed, hydrogen will be liberated at the surface of the lead plate, and the SO_4 group at the surface of the dioxide plate. At the former plate the lead sulphate is reduced to metallic lead, and sulphuric acid re-enters the solution ; at the latter, although the actions going on are numerous and complicated, the final result is that the lead sulphate is broken up, the dioxide reproduced, and sulphuric acid returned to the solution. We may imagine the SO_4 group as first decomposing water, reforming the acid and liberating oxygen at the surface of the plate, which then reacts according to the equation

$$O + PbSO_4 + OH_2 = H_2SO_4 + PbO_2.$$

Really several reactions are proceeding simultaneously.

While these processes are going on, no gas appears at either plate ; but when they are completed hydrogen and oxygen gases are freely evolved at the respective plates and the cell is then charged and again ready for use, the dioxide plate being dark brown in colour and the lead plate a light grey.

In outlining these operations we have purposely avoided chemical equations as much as possible, as being more likely to obscure the issue than otherwise. The student is not even

expected to believe in them too seriously, i.e. the actual formation of litharge (PbO), as an intermediate product during either charge or discharge, is very doubtful although convenient for the purpose of explanation. The actual change from dioxide to sulphate may be direct and vice versa.

The main thing to be remembered is that lead sulphate is formed at both plates during discharge as an essential factor in the working, and that it naturally tends to choke the action of the cell, both mechanically and also because it is a non-conductor. As long as this formation is not allowed to proceed too far, or the cell to stand too long before recharging, the sulphate is easily and completely reduced during the charging process; but it is a very remarkable and important fact that if these precautions are not observed, some change appears to take place in it which makes the sulphate almost irreducible, and the very substance upon whose formation the action of the cell depends then becomes its worst enemy. A badly "sulphated" cell is extremely difficult to deal with and is always a source of trouble. The exact nature of the change is very obscure, as is the exact composition of what we have termed "lead sulphate," for a number of complex sulphates exist; it may, however, be pointed out that if by any means the material ceases to be in good electrical connection with the plate, which from its porous nature is not unlikely to happen, it no longer forms part of the circuit, and no amount of charging will reduce it electrolytically, although possibly some such effect may be produced by the indirect and long-continued action of the gases evolved during the operation. In fact, the best remedy for sulphated cells is a long charging process with a small current.

Another effective cause of trouble is the presence of impurities in the cell. Just as "local action" in a primary cell is due to traces of other metals in the zinc or the chemicals used, so will such traces cause self-discharge in the plates of an accumulator, and hence it is well worth while taking infinite pains to ensure the purity of the materials and electrolyte. Even when these are pure to begin with there is danger due to the careless addition of water to make up for evaporation. Tap water must never be used, or even clean rainwater, for that may contain ammonia compounds which are extremely prejudicial to the cell.

Thus far we have referred to plates of lead and lead dioxide without considering the details of construction ; but it is evident that if a cell is to give out current for some time, i.e. if it is to have a reasonable capacity in ampere-hours, its plates must have a large surface area exposed to the liquid. This can be obtained partly by the usual multiple construction, i.e. building up the equivalent of one large plate out of a number of smaller ones placed side by side, connected together and interleaved with a corresponding set of the opposite polarity.

In an alternative and much more convenient plan the plates may have a very porous surface freely penetrated by the solution. On the other hand, this construction leads us into the practical difficulty that such porous masses are very liable to disintegrate through lack of mechanical strength.

The object of every manufacturer is therefore to design his plates so as to obtain the greatest amount of active surface consistent with sufficient mechanical strength, and obviously this will depend partly upon the use to which the cells are to be put. If carried about on moving vehicles, and thus exposed to jolting and vibration, they must be stronger than if they are never to be disturbed after once being set up.

At the present time practically all plates are either formed by what is known as the " Planté " process or modifications thereof, or are of the " pasted " variety.

In the first case we may start in the simplest way by immersing plates of ordinary sheet lead in dilute sulphuric acid and proceeding to charge them. This causes oxygen to be evolved at one plate and hydrogen at the other, the first plate becoming superficially coated with peroxide, and the latter being unaffected ; but the action soon stops, and is not perceptibly increased by prolonged charging. Planté's method was to reverse the direction of current and to keep charging first one way and then the other for a very long time, perhaps six months, thus alternately oxidising each plate and then reducing it to spongy metallic lead, and at each step biting deeper into the plate. When sufficient active material had been produced the process was stopped and the cell thenceforth used in the ordinary way with unidirectional charges. Plates formed in this manner have many excellent qualities especially

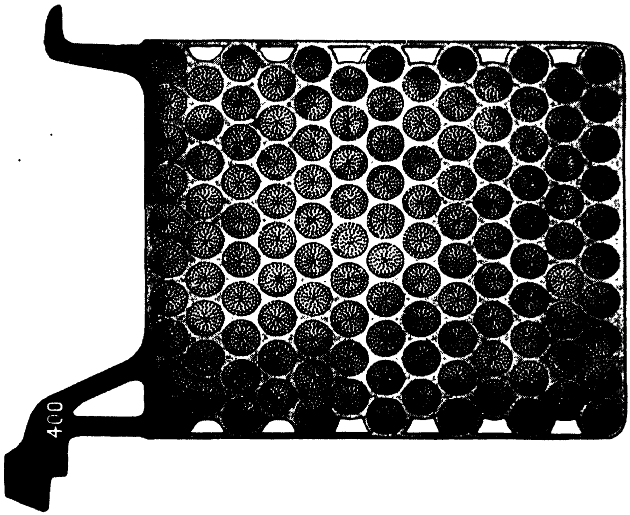
from the point of view of durability, for as active material is formed from the plate itself it is firmly attached and not likely to be easily dislodged. The only disadvantages are the slow process of formation and the small capacity obtainable for a given size and weight ; but as regards positives, at any rate, it is the method which in some form is universally adopted in the case of cells for heavy and varied work.

Negative plates formed in this way are not so good and durable as the positives. Evidently they are really positive plates whose dioxide coating has been reduced to spongy lead by reversal ; and for some reason they appear in course of time to alter in molecular structure and lose much of their porosity, thereby decreasing the capacity of the cell. It is for this reason that the negative plates are mostly of the pasted variety.

In more recent practice it is not usual to form positives by Planté's original method of reversal. It is not necessary unless both negatives and positives are to be formed simultaneously, and as a rule the plates which are to become positives are made up temporarily with dummy negatives, repeatedly charged and then discharged by completing the circuit, but the successive charges are always in the same direction. This period of formation has been much shortened by the use of nitrates and other substances in the forming solution, but it is always tedious, and may take six weeks or so of incessant charging.

An obvious improvement is to use corrugated instead of smooth plates, so as to obtain the maximum surface for a given total weight. This is done in an infinite variety of ways. In America the lead plates usually have suitable grooves cut into them mechanically, whereas in this country the metal is more often cast into the required shape.

Modern Planté plates consist of castings of pure lead, on the surface of which a film of lead peroxide (PbO_2) is formed by an electro-chemical process on the lines indicated above. In order to secure a large effective area, the plate is so designed that its actual developed surface may be from 8 to 10 times its apparent superficial area. The durability of this type of plate is due to the fact that as wear and tear gradually take place during service, further active material is formed out of the lead base to take the place of that which is lost. A special variation



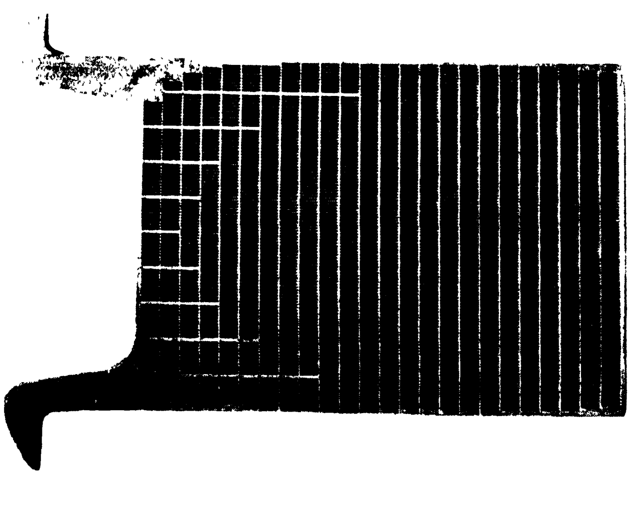


FIG. 25?

of the Planté positive plate is the Rosette type, manufactured by the Chloride Electrical Storage Company, Ltd.,[1] which is used in cases where very heavy work has to be dealt with. In this type of plate the grid is of lead, alloyed with a little antimony to give stiffness, and is perforated by a great many circular holes about $\frac{3}{4}$ inch in diameter, slightly countersunk on both sides. Into these holes are driven by hydraulic pressure "rosettes" formed by coiling up a crimped strip of thin lead into a spiral, and the plates are then formed by the process just described. The acid freely penetrates these rosettes and the charging converts them into dioxide which is securely keyed into place by the shape of the holes.

A Chloride-Planté positive plate and a Chloride-Rosette positive plate are shown in Figures 252 and 253 respectively, and plates thus made range in size from $3'' \times 4''$ to $16'' \times 45''$, the latter having a capacity of 446 ampere-hours at the 10-hour rate.

Pasted plates were invented by Faure in 1882, and their introduction marked the commencement of the commercial era for accumulators. In these the plates themselves are merely supports or grids, which serve as receptacles for the active substances.

The grids are made of lead, alloyed with a certain percentage of antimony to provide stiffness, and in the early days were so designed as to hold the paste in the form of small pellets. Modern grids for pasted plates may either be of the "lattice" or "box" type.

A pasted plate having a lattice type of grid is shown in Figure 254; the paste is held in continuous strips running from the top to the bottom of the plate and the horizontal ribs are staggered in order to retain the active material more securely. This type of construction provides good electrical contact between the active material and the grid.

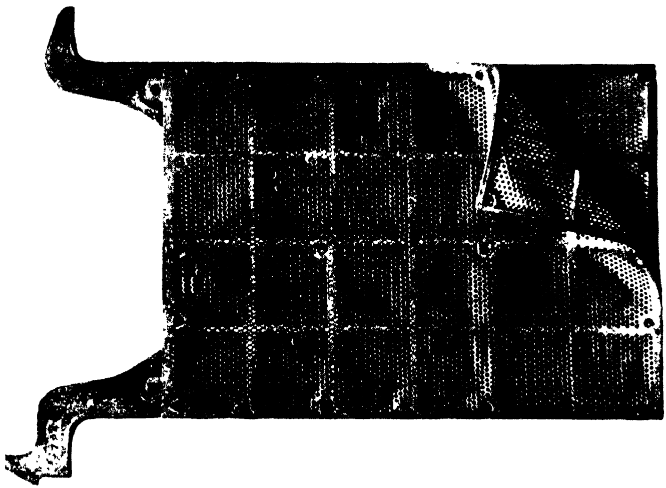
A pasted plate having a "box" type grid is illustrated in Figure 255, and it will be seen that in this type the active material is enclosed in a hollow grid faced with perforated lead gauze and is thus freely penetrable by the acid. The

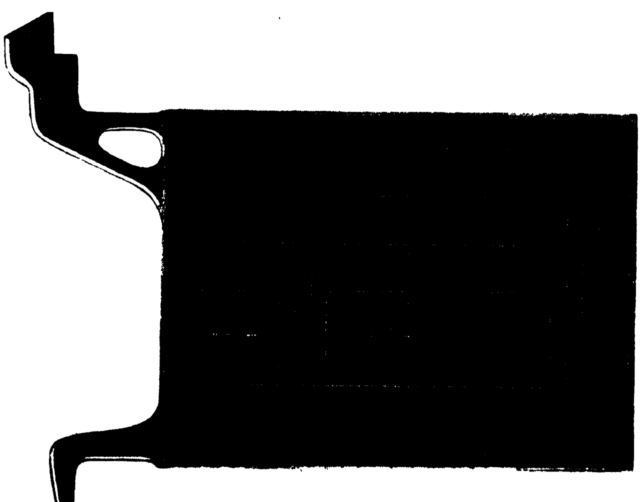
[1] The writer is greatly indebted to the Company mentioned for much of the information given in the following pages in connection with the construction and care of lead accumulators and also for the illustrations shown in Figures 252, 253, 254, 255, and 257.

grid is in two halves, each of which is filled with paste, and the two halves are placed together so that the pins on one side pass through the holes in the other and are then firmly riveted down. This type of construction is much used for the negatives of large stationary batteries and produces plates having a long life. The paste is made either of red lead or litharge mixed with dilute sulphuric acid and may contain some inert filler in order to add to the porosity of the finished article.

Pasted plates have the important advantages of requiring but a short "forming" process and of giving a much greater capacity for a certain weight than is obtainable from Planté plates. On the other hand, the active material is less securely fixed to the grids than is the case with Planté plates. Pasted plates are very largely used for both the positives and negatives of portable batteries and for the negatives of large stationary batteries.

When arranging a number of plates to form a complete accumulator, it is usual to employ a number of negative plates which exceeds the number of positive plates by one, thus having a negative plate at each end of the assembly. The several positive plates have their connecting lugs burned on to a connecting bar situated at one side of the cell while the several negative plates are burned on to a similar bar situated at the other side of the cell, the general arrangement being as shown in Figure 256. It is necessary to place separators between each pair of plates in order to minimise the risk of a short circuit occurring between them due to detached fragments of paste or to buckling of the plates (which is sometimes caused by excessive discharge rates). Modern separators usually take the form of thin sheets of very porous wood, which arrangement is found to give very perfect separation between the plates without unduly increasing the internal resistance of the cell. In small portable accumulators the plates commonly fit fairly tightly into the containing vessel, but in larger stationary accumulators the plates are usually suspended from the sides of the container as shown in Figure 256. In this figure it will be seen that a considerable distance is left between the bottom of the plates and the bottom of the vessel; this is necessary in order that the gradual accumulation of plate debris at the bottom





of the container shall not short-circuit the plates. When cells are to be connected in series to form a battery, the connection may be made by bolting the positive connecting bar of one cell to the negative connecting bar of the next cell by means of a lead-covered bolt. Alternatively, a burned connection may be used which, while giving greater electrical efficiency, is not so convenient. Containing vessels may be of celluloid for small portable accumulators, but for larger cells of the stationary type, glass or lead-lined wood containers are usual.

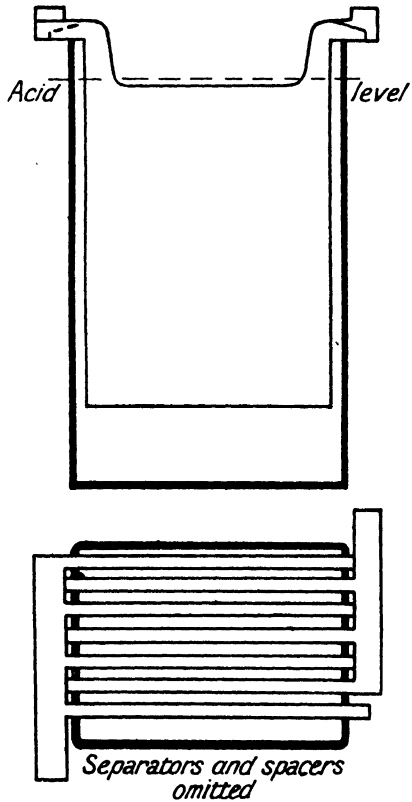


FIG. 256.

DISCHARGE RATES OF ACCUMULATORS

A certain accumulator can, of course, be discharged at various rates depending upon the amount of resistance in the external circuit. What may be termed a normal rate of discharge is one such that the cell becomes fully discharged (starting in the fully charged state) in a period of about eight hours. This process is sometimes referred to as discharging at the eight-hour rate. If the cell is discharged more rapidly (by allowing it to send a larger current) it may become run down in six hours, the discharge then being at the 6-hour rate. For special purposes (as for peak-load work in central stations) very high discharge rates, such as the 2-hour or even

the 1-hour rate, are sometimes used. Of course, such high rates of discharge impose very severe work on the plates, whose life is likely to be shortened unless they have been designed to stand up to such a service.

CAPACITY OF ACCUMULATORS

The storage capacity of an accumulator is usually expressed in terms of the ampere-hour and is found by multiplying the discharge current by the time during which the discharge can be maintained by the cell, commencing with the cell fully charged and carrying on the discharge until the voltage has fallen to the minimum safe value. Occasionally the capacity is expressed in terms of the watt-hour and the watt-hour capacity of an accumulator can be found by multiplying the ampere-hour capacity by the average voltage during discharge. The main factor governing the capacity of an accumulator is the active area of the plates, but it is very important to realise that the capacity of a certain accumulator depends very materially on the rate of discharge, as will be seen from the following table which gives the results of tests on a Chloride-Planté cell.

Discharge current. Amperes.	Duration of discharge. Hours.	Capacity. Ampere-hours.
10	10	100
16·6	5	83
23	3	69
50	1	50

CHANGES OF VOLTAGE DURING CHARGE AND DISCHARGE

The open-circuit voltage of a fully charged accumulator may be taken as about 2·1, but the P.D. at the terminals is a very variable quantity depending upon whether the cell is charging or discharging, on the magnitude of the charge or discharge current, and on the proportion of the full charge which is in the cell at the time of the test. Potential differences during charge will be higher than those during discharge since, in the former case, the voltage needed to drive the current through the internal resistance of the cell will be added to the E.M.F., while in the latter case it will be subtracted

from the E.M.F. The magnitude of the voltage drop in the cell due to internal resistance will be greater at high rates of charge or discharge and will exert a correspondingly greater effect on the P.D. of the cell.

Typical charge and discharge curves of a lead accumulator at various rates are shown in Figure 257. Dealing only with the numbers relating to normal rates, it is seen that when the charging current is put on to a discharged cell the P.D. at the terminals rises quickly to 2·15 volts, after which it continues

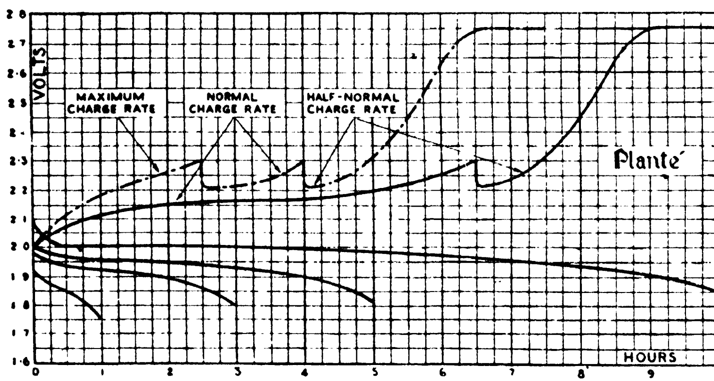


FIG. 257.

to rise steadily for some hours. As the charge approaches completion, the P.D. commences to rise more rapidly and may reach a value of, say, 2·7 volts. If the cell is then put on to discharge the P.D. will quickly fall to about 2·0 volts and will then continue to fall very gradually for the greater part of the time occupied by the complete discharge. As the discharge nears its end the P.D. will commence to fall rather more rapidly, and when it has reached 1·85 volts the discharge may be regarded as completed. Changes of the same general nature will take place during other rates of charge or discharge.

A knowledge of the P.Ds. of an accumulator under different conditions is very necessary when it is desired to arrange the installation of a battery of accumulators for any purpose. Consider the installation of a battery intended chiefly for use

during periods of light load in an isolated installation, the power being primarily obtained from a dynamo driven by an oil engine. The main circuit connections for the type of installation in mind are shown in Figure 258, from which it will be seen that even when the dynamo is directly supplying the chief portion of the demand, the battery is floating on the mains and the number of cells in use is settled by the positions of the arms of the double cell regulating switch. The necessary switches, fuses, and instruments are omitted

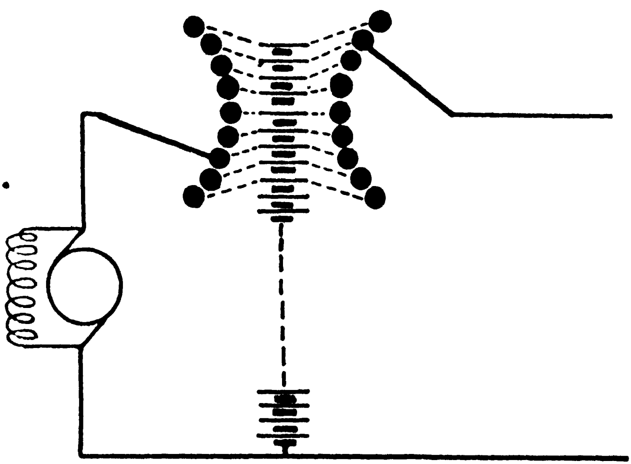


FIG. 258.

from the diagram as is also the automatic cut-out commonly used in such an installation to prevent the dynamo operating as a motor, due to a fall in generated voltage, and so discharging the battery.

Suppose that the lamp voltage is 230, then the total number of cells must be such as to be capable of supplying this voltage when the dynamo is not running and the cells are in their lowest state.

In this case the total number will be $\frac{230}{1\cdot85}=124.$

The minimum number of cells required will be such that they will give the correct voltage when they are on charge

and well up. Taking 2·4 as the voltage per cell under these conditions, the minimum number of cells in use will be $\frac{230}{2 \cdot 4} = 96$. The remaining 28 cells will be what are known as regulating cells and arrangements must be made to switch these in or out at will. If the lamps are never to be used when the battery is on charge, the number of regulating cells could be reduced. The dynamo should be capable of giving up to 2·7 volts per cell or $2 \cdot 7 \times 124 = 335$ volts in all.

The form of contact of the necessary cell regulating switch

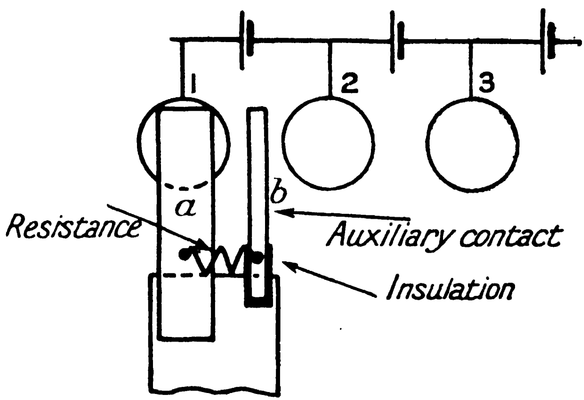


FIG. 259.

is of interest, and it is important that it should be such as will not, when being moved from stud to stud, either break the circuit (in which case there will be arcing and the lamps will flicker very badly) or short-circuit a cell. The contact consists of two parts (see Figure 259) which are separated from each other by insulation but are connected by a resistance coil of suitable magnitude. The spacing of the contacts is such that as the regulator is moved in the direction to increase the voltage the auxiliary contact *b* touches stud 2 before the main contact leaves stud 1, thus preventing discontinuity of supply. The breadth of the main contact *a* is too small to permit of it touching two studs at once and so short-circuiting a cell. After the desired regulation has been effected, the arm

should be left in such a position that while the main contact is on a stud, the auxiliary contact *b* is clear of a stud. The value of the resistance between the two studs should be such as will limit the local current during transition to a reasonable amount.

CHANGES OF DENSITY OF ACID DURING CHARGE AND DISCHARGE

It has already been stated that the strength of the acid in an accumulator falls during discharge and rises again during charge, and this causes corresponding changes in the density of the acid. These changes in density may be detected by an instrument known as a hydrometer and useful information concerning the state of the cell thereby obtained. When an accumulator is fully charged a typical value for the density of the acid is 1·21 and this falls fairly uniformly during discharge until, when the discharge is completed, the density is likely to be about 1·17. Thus, assuming the correct strength of acid is in the accumulator when fully charged, the density of the electrolyte gives a good idea as to the proportion of the full charge which is in the cell at any time.

A variable immersion hydrometer, such as is commonly used for battery work, usually consists of a flattened glass bulb with a comparatively narrow tubular stem. It is weighted so that it floats upright in the liquid and so (with a fully charged accumulator) that the greater part of the stem is clear of the acid. As the acid weakens during discharge and falls in density, the hydrometer becomes more and more immersed and the actual density of the acid at any time can be read off on a paper scale inserted in the narrow glass stem.

CARE OF LEAD ACCUMULATORS

Care should be taken that the acid is of the correct density, the plates fully covered and when, due to evaporation, it becomes needful to "top" up the cell, that only distilled water is used.

Cells should never be left standing in the discharged condition (if this is done sulphating is likely to result), but should be recharged immediately after a discharge. If the cells are not required for several months it is well to charge them up and then remove the acid from the plates. Completion of the

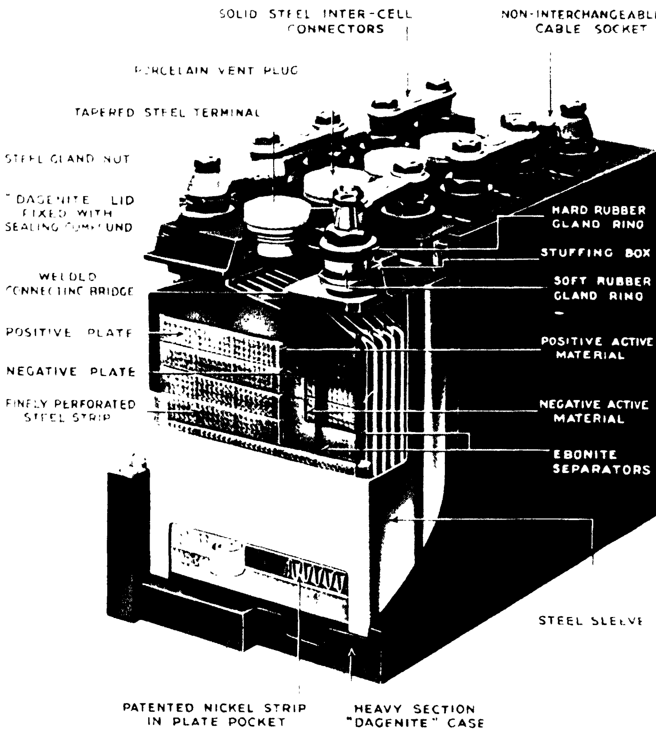


FIG. 260

To face page 426

charge is indicated by the P.D. of the cell, by the density of the acid, and by small bubbles of gas being given off copiously from the surfaces of both positive and negative plates. As a rule, charging should not be continued for more than 15 or 30 minutes after free "gassing" has commenced since, if this is done, the energy is wasted for the most part and the life of the plates shortened.

There are, of course, several sources of loss in an accumulator and the over-all efficiency is likely to be of the order of 85 per cent to 90 per cent based on the input and output in ampere-hours.

THE ALKALINE ACCUMULATOR

Accumulators containing an alkaline electrolyte are now being used to a considerable extent, and, for certain purposes, have well-marked merits. One well-known type of alkaline cell, known as the "Nife" accumulator, is made by Messrs. Batteries Ltd., of Redditch, to whom we are indebted for information and for Figures 260 and 261. In this cell the active material of the positive plate is nickel hydroxide (mixed with other ingredients to improve the conductivity) which is contained in envelopes of perforated nickelled steel which are carried by steel frames. The active material of the negative plate consists essentially of iron and cadmium oxides contained and mounted in a manner similar to that used in the case of the positive plate. The electrolyte is a solution of potassium hydrate in distilled water made up to have a density of 1·19. The separators are of hard rubber and the containing vessel is made of steel with welded joints.

The chemical changes during charge and discharge are complicated, but essentially, during discharge, the positive plate becomes less highly oxidised while the negative plate becomes more highly oxidised, changes of the opposite nature taking place during charge. It is of particular interest to note that the density of the electrolyte does not change during charge or discharge. One of the difficulties met with in alkaline accumulators has been to keep down the internal resistance of the cell and, in the type under notice, not only are the active materials chosen with this end in view, but, in addition, zigzag strips of nickel are inserted in the pockets of active material, a method which has been found to be very effective. Such a strip is clearly seen in the lower part of

Figure 260, which represents a battery arranged for use on a motor-car for lighting and starting purposes.

Perhaps the chief disadvantage of the alkaline cell is the comparatively low P.D. which, on ordinary discharge rates, is of the order of 1·2 volts. The general nature of the changes in P.D. during charge and discharge at various rates is similar to that of the lead accumulator and is shown in Figure 261. On the other hand, the alkaline cell is very

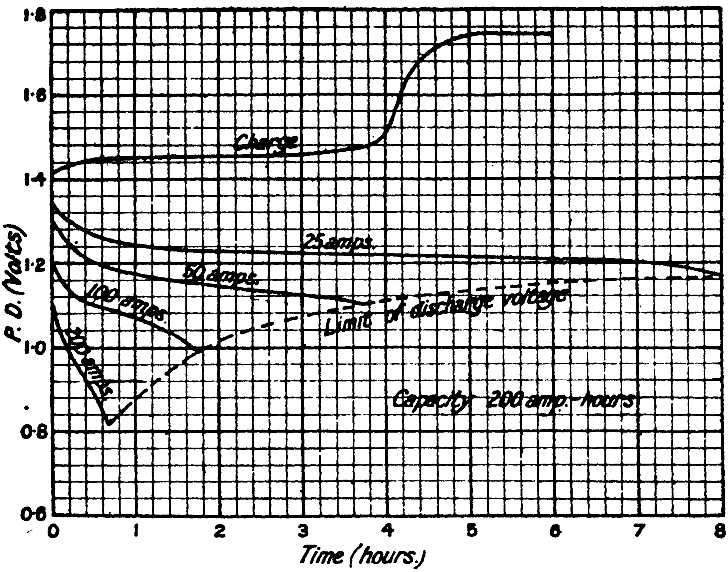


FIG. 261.

capable of standing rough mechanical (i.e. vibration) and electrical (i.e. heavy discharge rates and standing in the discharged condition) usage without harmful effects. For a certain storage capacity (more particularly if expressed in ampere-hours) the weight and bulk of the alkaline cell is less than that of the lead cell.

It should be noticed, when using alkaline cells, that, though the hydrometer is of use for ascertaining if the electrolyte is of correct strength, it is useless as a means for ascertaining the state of charge or discharge of the battery.

NUMERICAL EXAMPLES

The Electric Circuit

1. Determine the resistance of a lamp which takes 0·261 ampere when connected across mains at a voltage of 230.

2. The resistance of the field coil of a shunt dynamo is 320 ohms. What will be the value of the exciting current when the P.D. of the machine is 220 volts ?

3. A cable has a resistance of 0·336 ohm per mile. What will be the voltage drop over a length of 600 yards of this cable when a current of 80 amperes is flowing through it ?

4. A battery of accumulators sends a current of 8 amperes through a circuit. When an additional resistance of 4 ohms is placed in the circuit, the current falls to 6 amperes. What was the original resistance of the circuit ?

5. A battery has an E.M.F. of 4·1 volts but, when sending a current of 12·5 amperes through an external resistance, the P.D. is 3·85 volts. Calculate the value of the external resistance and of the internal resistance of the cell.

6. A battery of 24 accumulators, each having an E.M.F. of 2·05 volts and an internal resistance of 0·01 ohm, is connected in series with an external resistance on to a voltage of 70. What should be the value of the external resistance if the charging current is to be 30 amperes ? What would be the P.D. of each cell during charge and the P.D. of each cell during discharge with the same value of current ?

7. A battery comprising four cells connected in series, each having an E.M.F. of 1·07 volt and an internal resistance of 0·3 ohm, is used to send current through an external resistance of 0·8 ohm. Determine the current flowing through the resistance and the P.D. of the battery. What would be the corresponding values if the cells were in parallel ?

8. How would you couple up four cells, each having an E.M.F. of 1·4 volt and an internal resistance of 2 ohms, in order to send a maximum value of current through an external resistance of 2 ohms ? What would be the value of the current ?

9. Resistances of 3 and 4 ohms respectively are connected in series and joined on to a cell having an E.M.F. of 2·05 volts and an internal resistance of 0·05 ohm. Calculate the current flowing and the P.D. across each resistance.

10. A galvanometer has a resistance of 1·0 ohm and requires a current of 0·01 ampere to give a full-scale deflection. What resistances should be placed in series with the movement in order that full-scale readings may be obtained for applied voltages of 15 and 150 respectively?

11. If the galvanometer mentioned in the previous example is to be shunted for use as an ammeter, what should be the resistances of the shunts for full-scale readings of 7·5 and 15·0 amperes respectively?

12. A battery, composed of 56 accumulators each having an E.M.F. of 2·1 volts and an internal resistance of 0·002 ohm, is connected in series with a resistance of 1·0 ohm and charged from mains at a voltage of 150. Calculate the magnitude of the charging current.

13. A three-wire D.C. feeder cable has 0·1 ohm resistance in each of its outer cores and 0·2 ohm in its middle core and the supply voltage at the station end of the cable is 240 on each side of the system. If the currents on the positive and negative sides of the system are 100 and 80 amperes respectively, determine the voltages on the two sides of the system at the far end of the feeder.

14. The members of a network arranged in the manner of a Wheatstone's Bridge have the following resistances: AC = 1 ohm, AD = 2 ohms, CB = 2 ohms, and DB = 1 ohm. A cell having an E.M.F. of 2 volts and of negligible resistance is connected across A and B, and a resistance of 1 ohm in series with an ammeter across C and D. Determine the current flowing through the ammeter.

15. The two sides CB and AD of a wire rectangle each have a resistance of 2 ohms while the two sides CA and BD each have a resistance of 1 ohm. If the points A and B are joined by a resistance of 3 ohms, determine the resultant resistances between A and B and between C and D.

16. Two cells A and B are connected in parallel (their positive poles being connected together) to send a current through a resistance of 2·4 ohms. If the particulars of the cells are as given below, determine the current sent by each cell.

	E.M.F. (volts).	Internal resistance (ohms).
Cell A	1·8	0·8
Cell B	1·4	0·4

Resistance

1. Calculate the resistance of a strip of annealed copper whose cross-section measures 4″ × 0·25″ and which is 18′ long.

2. It is found that 80 yards of iron wire having a diameter of 0·1″ has a resistance of 1·4 ohms. Calculate the resistivity of the iron.

3. What length of manganin wire having a diameter of 0·122 cm. will be required to give a resistance of 8 ohms ?

4. A round copper conductor 40 metres long is required to have a resistance of 0·12 ohm. What should be its diameter ?

5. A coil for a field magnet is composed of copper wire 0·036″ in diameter. If there are 800 turns, the average diameter of each turn being 5″, calculate the resistance of the coil.

6. A coil of copper wire composed of 560 turns, the mean diameter per turn being 15 cms., is required to have a resistance of 180 ohms. What should be the diameter of the wire employed ?

7. Calculate the resistance per mile of a cable composed of 19 strands of copper wire each 0·028″ in diameter.

8. A cable composed of 7 strands of copper wire, each 0·09144 cm. in diameter, is used to convey current from a dynamo to lamps taking 30 amperes situated 72 metres away. If the P.D. at the terminals of the dynamo is 115 volts, what will be the voltage applied to the lamps ?

9. A dynamo giving a P.D. at its terminals of 122 volts is used to supply current to lamps situated ½ kilometre distant from the dynamo. If the lamp voltage is 115 and the current required is 42 amperes, what area of cross-section should be used for the cable ?

10. A field coil when cold has a resistance of 162 ohms, and after current has been passed through it for some time the resistance rises to 186 ohms. Determine the approximate value of the average temperature rise of the coil.

11. A copper wire has a resistance of 24 ohms at 18° C. What will be the value of its resistance at 0° C., -10° C., and 50° C. respectively ?

12. A copper field coil at 15° C. takes 0·88 ampere from 230-volt mains. What current will the coil take from the mains if its average temperature rises to 60° C. ?

13. A wire 880 yards long has a diameter of 0·25″ and a resistance of 0·44 ohm. Calculate the resistivity of the material of which the wire is composed.

14. Calculate the resistance of a copper wire 86 yards in length and having a diameter of 36 mils.

15. Resistances of 2, 4, and 5 ohms are connected in parallel and the combination connected in series with a resistance of 3 ohms and a battery having an E.M.F. of 10 volts and an internal resistance of 0·5 ohm. Calculate the current flowing in each resistance and the P.D. of the battery.

16. A piece of cable 80 yards long, composed of 19 strands of copper wire each 0·036″ in diameter, is connected in parallel with another piece of cable 110 yards long composed of 7 strands of copper wire each 0·064″ in diameter. If the total current through the combination is 80 amperes, calculate the current through each cable.

17. Three lengths of cable having resistances of 0·04, 0·03, and 0·02 ohm respectively are connected in parallel and a current of 150 amperes sent through the combination. Calculate the current through each resistance and the P.D. across the cables.

18. An aluminium wire 5 metres long and 0·2 cm. in diameter is to be shunted by a copper wire so that the combination will have a resistance of 0·04 ohm. If the copper wire is 6 metres in length, what should be its diameter ?

Power and Energy

1. The power required to drive a certain motor is 10 kW, the resistance of the mains used to convey current to the motor being 0·24 ohm. Calculate the power wasted in the mains (*a*) if the supply voltage is 230, (*b*) if the supply voltage is 460.

2. The particulars given below relate to the charge and subsequent discharge of a battery of accumulators. Determine the values of the ampere-hour and watt-hour efficiencies.

	Current (amps.).	Average P.D. (volts).	Time (hours).
Charge	20	280	8
Discharge	35	230	4

3. Two resistances are connected in parallel and when a voltage of 110 is applied to the combination the current is 21 amperes. If one of the resistances absorbs 1600 watts, what is the magnitude of the other resistance ?

4. A motor-generator whose efficiency is 70 per cent takes 4 amperes at 230 volts. If its output voltage is 12, how many amperes will it supply ?

5. What is the least voltage at which a power of 80 kW can be transmitted through mains having a resistance of 0·012 ohm if the power loss in the mains is not to exceed 2·5 kW ?

6. An electric heater for a 230-volt circuit has a resistance of 45 ohms. If the cost of energy is 0·6 penny per kWH, calculate the cost of running the heater for 6 hours per day for one week.

7. An electric car running at 15 miles per hour takes 60 amperes at a voltage of 550. If the cost of energy is 0·75 penny per B.O.T. unit, determine the cost of energy per car-mile.

8. In a shunt motor the resistance of the armature circuit is 0·25 ohm and the resistance of the field circuit is 120 ohms. If the motor takes 56 amperes at 230 volts, determine the power lost owing to the resistances of the two circuits.

9. An installation on a supply voltage of 230 comprises sixty 40-watt lamps, twenty 60-watt lamps, and a radiator taking 9 amperes. How much will it cost to run for 60 hours if the price of energy is 1·25 penny per B.O.T. unit ?

10. Power is to be transmitted by direct current over a distance of 5·0 miles, the resistance of the cable used being 0·08 ohm per mile. If the voltage at the receiving end of the line is 440, calculate the efficiency of the transmission when 10, 20, and 40 kW are being transmitted respectively.

11. It is desired to re-wind an electric iron, which has been taking 0·6 kW on a 250-volt circuit, for use on a 220-volt circuit. What will be the appropriate value for the resistance of the iron under the new conditions ?

12. What current will be taken by a 20-H.P. motor if it is running at full load on a 230-volt circuit with an efficiency of 85 per cent ?

13. How many H.P. will be required to drive a dynamo if its efficiency is 85 per cent and it is supplying power to eight hundred 100-watt lamps ?

14. The input of a motor is 24 amperes at a voltage of 460. Calculate its output in H.P. if its efficiency is 87 per cent.

15. The therm (a unit used in connection with gas supply) is equal to 100,000 British Thermal Units. How many kilowatt-hours are there in one therm ?

16. A generator driven by a water-turbine gives a terminal voltage of 480. The turbine is fed with 200,000 gallons of water per hour at a head of 200 feet. If the efficiency of the turbine and generator is 65 per cent and 89 per cent respectively, calculate the output of the turbine and of the dynamo. What current may be taken from the dynamo ?

17. A tramcar weighing 11 tons moves along level rails at a speed of 14 miles per hour. If the track and windage resistance to be overcome is 35 lbs. per ton, calculate the power and current taken by the car. The supply voltage is 480 and the efficiency of the motors and gearing may be taken as 75 per cent.

18. A motor is to be installed in connection with a lift which is required to raise a load of 600 lbs. at a rate of 6 feet per second. What is the value of the output which will be taken from the motor if the efficiency of the lift and gearing is taken as 75 per cent ? If the supply voltage is 230 and the efficiency of the motor 87 per cent, calculate the current taken from the mains.

19. A dynamo absorbs 38·4 H.P. when it is supplying current to eighty-six 300-watt lamps. What is its efficiency ?

20. What will be the cost of heating 4 pints of water from 60° F. to 212° F. in an electric kettle having an efficiency of 80 per cent if energy costs 0·5 penny per unit ?

21. What voltage must be supplied to a resistance of 40 ohms in order that sufficient heat may be developed to heat 3 kilograms of water from 15° C. to 100° C. in 8 minutes ?

22. A water-cooled resistance of 12·5 ohms is placed across 230-volt mains. How many pounds of water per minute will be required to cool the resistance if the temperature rise of the water is limited to 40° F. ?

23. A motor-driven pump is required to raise 10,000 gallons of water per hour through a height of 120 feet. If the over-all efficiency of the motor and pump is 45 per cent, calculate the power and current taken by the motor if the line voltage is 230.

Direct Current Dynamos and Motors

1. Draw a diagram of a ring winding, having 36 conductors, in a six-pole field, showing the directions of magnetic lines, voltages, and currents. Show also the polarity of the brushes and the direction of current in the external circuit.

2. A lap-wound armature for a four-pole field system is to have 48 conductors. Choose appropriate conductor pitches, and draw up a winding table.

3. Choose a suitable number of armature conductors for a lap winding for a six-pole generator to give 250 volts when running at 850 R.P.M., if the flux per pole is 2,500,000 lines.

4. Choose suitable conductor pitches for the winding in Question 3 and state how many commutator segments would be required (assume the winding to have one turn per coil).

5. The total number of armature conductors in a lap winding for a four-pole field is 440. What should be the value of the flux per pole in order that the armature may generate 220 volts when running at a speed of 1000 R.P.M. ?

6. The numbers in the table represent the no-load magnetisation curve of a generator when run at 800 R.P.M. If the shunt field circuit has a resistance of 135 ohms, to what voltage will

the machine build up when run as shunt generator at that speed ? Neglect any loss of voltage in the armature due to the field current.

Field current (amps.).	0·1	0·2	0·4	0·8	1·3	2·0
P.D. of armature (volts).	40	71	110·5	166	199·5	217

7. To what voltage will the machine dealt with in Question 6 build up if the resistance of the field circuit is increased to 160 ohms and the speed increased by 20 per cent ?

8. What will be the frequency of the voltage obtained from a six-pole alternator running at 1000 R.P.M. ?

9. An anchor ring of circular cross-section has internal and external diameters of 20 and 24 cms. respectively. If it is over-wound with 1000 turns each carrying 1·6 ampere, calculate the flux density in the iron and the total flux round the ring. Assume the permeability of the iron to be 500.

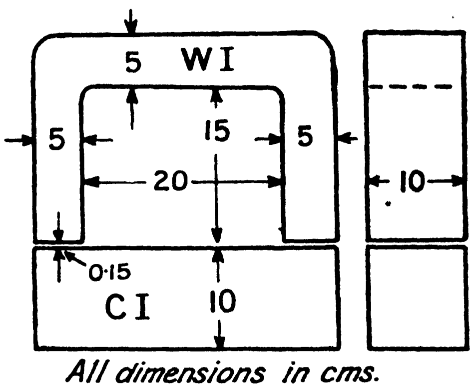


FIG. 262.

10. An anchor ring of rectangular cross-section has internal and external diameters of 25 and 30 cms. respectively, the depth of the ring being 6 cms. If the ring is composed of wrought iron, calculate the ampere-turns needed to produce a total flux of 225,000 lines round the magnetic path. If the ring is wound with 800 turns, what current would be needed ? The permeability of the iron may be obtained from Figure 95.

11. An anchor ring of circular cross-section has internal and external diameters of 20 and 24 cms respectively and has, in its circumference, an air gap 0·15 cm. long. If the magnetic circuit

is wound with 1600 turns, calculate the total ampere-turns and current required to drive a flux of 45,000 lines round the ring. It may be assumed that 12 ampere-turns per cm. are required to drive the flux density indicated through the iron.

12. Calculate the ampere-turns needed to send a flux of 700,000 lines round the magnetic circuit shown in Figure 262. Use the magnetisation curves given in Figure 128.

13. The armature of a D.C. motor has a resistance of 0·25 ohm and runs at a speed of 800 R.P.M. when 10 amperes is flowing in the armature circuit. Calculate the value of the back E.M.F. of the armature if the voltage of the supply is 230. At what speed will the motor run if the armature current increases to 50 amperes and the supply voltage and field strength remain unaltered?

14. Calculate the flux per pole necessary in order that the motor to which the following particulars apply may run at a speed of 1000 R.P.M. when taking an armature current of 40 amperes.

Type of armature winding	Lap.
Total number of conductors on armature	440.
Resistance of armature circuit	0·2 ohm.
Voltage of supply	230.
Number of poles	4.

15. Calculate the full-load and no-load speeds of the motor to which the following particulars apply:

Number of poles	4.
Type of armature winding	Lap.
Total armature conductors	1192.
Flux per pole	$0{\cdot}88 \times 10^6$ lines.
Supply voltage	220.
No-load current armature current	4 amperes.
Full-load current armature current	16 amperes.
Armature resistance	0·5 ohm.

16. A D.C. motor when running light takes 4 amperes at 250 volts. If the field resistance is 200 ohms, calculate the output and efficiency when the total motor current is 10 amperes and also when it is 20 amperes. Armature resistance = 0·8 ohm.

17. Calculate the input and efficiency of the dynamo to which the following particulars apply when giving output currents of 20 and 60 amperes respectively.

Terminal voltage	250.
Fixed losses due to friction and core	500 watts.
Field resistance	125 ohms.
Armature resistance	0·18 ohm.

APPENDIX

RECENT PROGRESS IN ELECTRIC DISCHARGE LAMPS

Since the last edition of this book was printed, considerable progress has been made in the production and use of lamps of the electric discharge type. New types have been introduced and earlier types have been improved or have passed out of commercial use. It has been thought desirable, therefore, to describe the newer types of such lamps and to indicate their characteristics and relationships to each other. Stress has been laid on the practical operation of the lamps rather than upon the complicated physical phenomena arising in connection with glow and arc types of electric discharge.

The prototype of all electric discharge lamps is the Geissler tube which has been used for scientific purposes for very many years. In this device an electric discharge is passed through a glass tube containing a gas at a pressure of a few millimetres of mercury and a typical form taken by the discharge is indicated in Figure A.

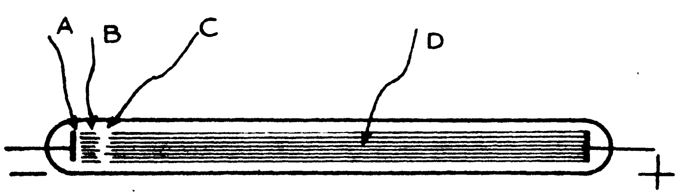


Fig. A.

The luminous rod-like portion D, which usually occupies the greater part of the length of the tube is known as the positive column and its colour is characteristic of the gas contained in the tube. C is an ill-defined dark region known as the Faraday dark space. The luminous part B is known as the negative glow, while the dark space A is referred to as the Crookes' dark space. The relative sizes of these portions may be controlled and, in fact, certain portions may be supressed, by modifying the nature and pressure of the gas, the length of the tube, and the magnitude of the current passing through the tube.

It should be noted that all electric discharge lamps make use of an unstable conducting medium and this fact necessitates the use of a stabilising resistance or some equivalent device in series with the lamp in order to ensure that the current remains reasonably constant during operation. On alternating current circuits a reactance in the form of a choking coil is usually employed and this, while minimising loss of power, results in a power factor which is less than unity. This low power factor can be improved, if desired, by using a condenser in parallel with the lamp and coil (see page 245). A typical value of power factor when no condenser is employed is of the order of 0·6 and by using a condenser it may well be brought up to 0·9.

Most commercial types of electric discharge lamps utilise the light emitted from the positive column but in the Osglim lamp (already described on page 359) the negative glow is utilised, the positive column being suppressed by attention to such points as the nature of the gas used, the gas pressure employed, and the distance between the electrodes.

Lamps which employ the positive column as the luminous source may be divided into two groups :—

1. Those in which the temperature of the cathode (in alternating current circuits each electrode becomes the cathode in turn) is comparatively low.

Such lamps are known as cold cathode lamps and are, in general, characterised by the use of high voltage, small current and long tubes. The discharge obtained is of the nature of an electric glow and is of low intrinsic brilliance and moderate luminous efficiency.

2. Those in which the temperature of the cathode is maintained at a high value either by heat from the discharge itself or by heating the cathode, which is arranged in filament form for the purpose, by current obtained from an auxiliary filament transformer. The use of a hot cathode ensures a plentiful emission of electrons thus promoting the flow of current through the tube. It is important to note that the direction of flow of electrons in a tube is opposite to the conventional direction of current flow. Hot cathode lamps employ a discharge of the nature of an arc and are characterised by the use of larger currents, lower voltages and shorter tubes. A rough idea of the relative characteristics of the two types is given in the following table. The numbers stated do not refer to any specific lamps and are intended to give a general impression only.

Type of lamp	Pressure (volts)	Current (amps.)	Length of tube	Efficiency (lumens per watt)
Cold cathode	1500	0·05 to 0·15	12 feet	10 to 15
Hot cathode	150	1·0 to 3·0	8 inches	35 to 70

COLD CATHODE LAMPS

Some information concerning cold cathode lamps has been given on page 359. They are now employed chiefly for electric sign purposes. The gas neon is still largely used when light of a reddish colour is required but colours toward the blue end of the spectrum are largely produced by using mercury vapour in conjunction with tubes of suitably tinted glass. The high alternating voltage employed is produced by transformers and the design of the high tension circuit is such that a striking voltage some 50 per cent. higher than the running voltage is available. The reactance of the high tension circuit also gives the stability necessary for steady flow of current. Such signs are often left working after premises are closed and the high tension circuit might cause danger to firemen should a fire occur in the building. To obviate this it is usual to put an additional switch, connected on the low tension side of the

transformer, on the outside of the premises in such a position that it is readily accessible to the firemen though not to the general public.

HOT CATHODE LAMPS

The most important types of hot cathode lamps include the high pressure mercury vapour lamp, the sodium lamp, and flood lighting lamps using neon gas or mercury vapour at low pressure.

The sodium lamp employs cathodes which are heated by the arc itself and is characterised by a very high luminous efficiency due to some extent to the fact that the radiation in the visible part of the spectrum is confined to lines in the yellow portion to which the eye is very sensitive. Efficiencies so high as 70 lumens per watt are obtainable, but the colour of the light militates against the use of the sodium lamp for general purposes, it is, however, used for road lighting and similar purposes.

Hot cathodes are also used in certain types of lamps which have been developed for flood lighting in colour. Neon gas is used in tubes for the production of red light and low pressure mercury vapour in conjunction with tubes of suitably tinted glass for certain other colours, advantage being taken of the fact that, apart from the red end, the lines in the spectrum of glowing mercury vapour are widely distributed over the visible portion. The electrodes in these lamps are in filament form and are heated, particularly at starting, by current obtained from low voltage filament transformers. The efficiency of such lamps is of the order of 10 to 15 lumens per watt.

It would appear that the most promising type of hot cathode lamp for general illuminating purposes is the high pressure mercury vapour lamp. The early types of mercury vapour lamp using the hot cathode had a low vapour pressure (of the order of a few millimetres of mercury). It was found that higher efficiencies and a more compact arrangement could be obtained by using higher vapour pressures and in the lamp now to be described the vapour pressure, when hot, is somewhat less than one atmosphere. Figure B shows the

arrangements and connections of the high pressure Mazda Mercra lamp made by the British Thomson-Houston Company.

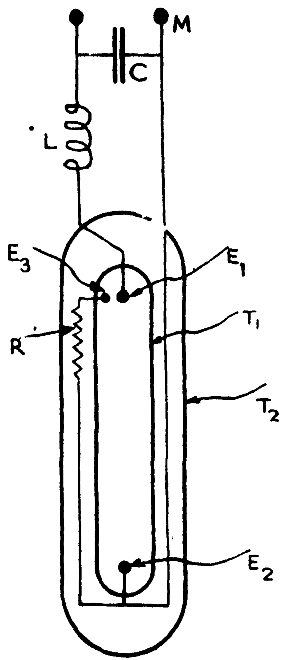


FIG. B.

The inner tube T_1 is of glass and contains, when cold, a small quantity of liquid mercury and some argon at low pressure. There will be very little mercury vapour in the tube until it becomes hot. The two main electrodes E_1 and E_2 are composed of pellets of a material which, when hot, gives a copious electronic emission. These pellets are mounted in frames made of tungsten wire. In addition, near one of the main electrodes, is a starting electrode E_3 connected, *via* a 50000 ohm resistance R, to the other main electrode of the lamp. Round the part already described is an outer glass jacket T_2, the space between the two glass bulbs being filled with a gas at a low pressure, the arrangement serving as a heat conserving device. To stabilise the arc a choking coil L is inserted in series with the main electrodes, and the condenser C shown in parallel with the lamp is used to improve the power factor of the circuit (see page 245) and is not an essential feature of the lamp itself.

When the normal supply voltage is switched on to the lamp a strong electric field is produced between the starting electrode and the adjacent main electrode and a discharge takes place through the argon gas between these points. The discharge spreads to the region between the main electrodes which together with the mercury in the inner bulb gradually warm up. Thus a copious electronic discharge soon becomes available from both main electrodes and the tube gradually becomes filled with mercury vapour which takes over the

duty of carrying the electric discharge and after a few minutes the lamp gives its full light output having the nature characteristic of mercury radiation.

It should be noted that if the lamp is switched off, it will not re-start if switched on again immediately. It must first be allowed time to cool somewhat in order that the vapour pressure in the lamp may fall to such an extent as will permit the re-striking of the arc. A lamp of this type working on an ordinary line voltage of 230 and taking 400 watts gives an efficiency of some 45 lumens per watt. It is likely that in the future still higher vapour pressures (10 to 20 or even more atmospheres) will be employed in mercury vapour lamps since it has been found that this condition permits of still higher efficiencies and more compactly arranged lamps.

COLOUR CONTROL OF LIGHT FROM ELECTRIC DISCHARGE LAMPS

It has already been pointed out that electric discharge lamps suffer from the disadvantage that the light produced is concentrated in a few wave lengths only which are characteristic of the particular vapour used. Thus, in the case of lamps using sodium vapour, the light is yellow and practically monochromatic which has the effect of eliminating colour distinctions in objects viewed in light emitted from this type of lamp. Lamps using mercury vapour emit a light with a more general distribution of lines over the range of the visible spectrum but unfortunately there is a great deficiency of red rays. The radiation, however, is rich in ultra violet rays (see Plate X facing page 348) and the importance of this will be seen later. Before considering methods which are available for improving colour rendition by electric discharge lamps it is necessary to stress the fact that a missing colour cannot be added to a light by the use of ordinary shades or screens which appear, in daylight, to be of the missing colour. Such devices appear coloured solely due to the fact that they are especially able to reflect or transmit the particular colour in question (other colours being largely absorbed) and if this colour is not present in the incident light the reflectors or shades will no longer appear to be of their characteristic colour and will be quite

useless for colour correcting purposes. If the experiment is actually tried it will be found that little light of any colour will be transmitted or reflected due to the absorption of the colours which are available from the lamp.

So far as lamps using sodium vapour are concerned there appears little prospect of the development of any method offering practical possibilities of colour correction. The position is, however, very different in the case of lamps using mercury vapour and several methods are available.

Perhaps the most obvious method is to make use of a combination of a mercury vapour lamp and a tungsten filament lamp. The amount of red in the light of an uncorrected mercury vapour lamp is of the order of 1%. In daylight the amount of red is about 15% while a tungsten filament lamp gives light containing about 25% of red. Thus, if a filament lamp is operated in conjunction with a mercury vapour lamp, the light from the combination contains a nearer approach to the red content of daylight than is obtained from the mercury vapour lamp alone. Unfortunately this result is of necessity accompanied by a considerable fall in the overall efficiency as compared with that obtained from the simple mercury vapour lamp.

Another expedient adopted to obtain a larger proportion of red rays is to introduce a proportion of cadmium with the mercury in the tube. In this way a red content of some 5·5% is obtained in the light but it is again accompanied by a serious fall of efficiency to a value something like a half that obtained in the simple mercury vapour lamp. More recently very successful attempts have been made to overcome the deficiency of red rays in the mercury vapour lamp by using the phenomena of fluorescence and phosphorescence which are often jointly referred to as luminescence. It has long been known that when certain materials are subjected to ultra violet rays, in which it will be remembered the light emission from the mercury vapour lamp is very rich, the energy in the ultra violet rays is re-emitted from the material at a lower frequency which, for a suitable substance, lies in the visible portion of the spectrum. If the material emits visible rays only while subject to the incidence of the ultra violet rays it is said to be fluorescent. Some substances continue to glow

when removed from the incidence of the ultra violet rays and these are said to be phosphorescent. Substances may be both phosphorescent and fluorescent and both properties are useful for colour correction in conjunction with mercury vapour lamps. In addition, phosphorescence may be useful in minimising flicker. Amongst luminescent materials may be mentioned cadmium tungstate (yellow), zinc silicate (green) and zinc phosphate (red).

Luminescence is particularly effective with low pressure mercury lamps because of the high proportion of ultra violet rays present in the emission from such lamps. Further, owing to the comparatively low temperature, the luminescent powders can be placed in the most effective position which is inside the tube. A wide range of colours can be obtained and when the most suitable powders are used there is a very considerable increase in the efficiency as compared with that of the simple low pressure mercury vapour lamp.

The Mazda Fluorescent Lamp, manufactured by the British Thomson-Houston Company, is an example of the use of luminescence in a low pressure mercury vapour lamp. In this lamp, which works on the ordinary mains voltage, the whole of the light output is obtained by fluorescence and is of daylight quality. An overall efficiency of 35 lumens per watt is obtained. The circuit and mode of starting this lamp are of interest and the former is shown in Figure C.

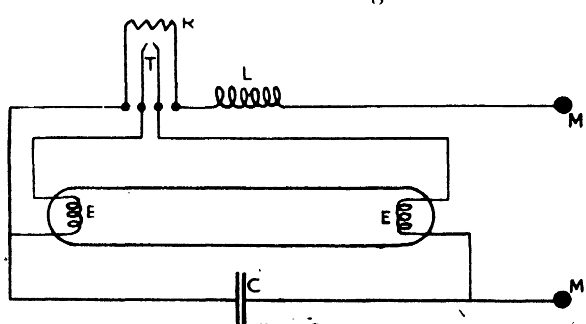


Fig. C.

When cold the contacts of a thermostat T are closed thus short-circuiting the electrodes E. When the main switch is closed a starting current, higher than the running current,

flows through the helices forming the electrodes E, heating them to a temperature sufficiently high to produce thermionic emission, and also through the resistance R in the thermostat. After a few seconds the rise in temperature of the thermostat is sufficient to open the thermostat contacts thus removing the short-circuit between the electrodes E and the discharge between the electrodes is started by the induced pressure produced. C is a condenser to suppress arcing at the thermostat contacts and L is the usual choking coil. The power factor of the lamp may be raised, if desired, by placing another condenser of 8 microfarads capacitance across the mains in the position corresponding to the condenser shown in Figure B.

The Osira Fluorescent Tubular Lamp manufactured by the General Electric Company is another example of the application of this type of luminescence. This Company also make Osira Fluorescent Tubes, which work on high voltage, and are used for illuminating and decorative purposes. They are obtainable in a variety of colours and in some tubes, it is interesting to note, discharge through neon gas, in place of mercury vapour, is the actuating cause of the fluorescence.

High pressure mercury vapour lamps have a smaller proportion of ultra violet rays in their emission than low pressure lamps but the proportion is amply large enough to make the use of luminescence worth while. A difficulty with these lamps is the high operating temperature and on this account it has been found necessary to place the powder on the inside of the outer envelope. This prevents full use being made of the ultra violet rays since a proportion of them will be absorbed by the inner glass tube. Good results have been obtained with Mercra lamps by using a small proportion of cadmium with the mercury together with luminescent powder on the tube.

STROBOSCOPIC EFFECT WITH ELECTRIC DISCHARGE LAMPS

The light from a discharge lamp, due to the small thermal capacity of the glowing gas, undergoes large changes of intensity during each cycle of current and this may produce what is known as a stroboscopic effect when used to illuminate running machinery. This happens when the speed of a wheel

has certain frequency relationships to the frequency of the supply voltage and may result in a moving wheel appearing to be at rest thus introducing a certain element of danger of a mechanical type.

It will be only occasionally that the necessary synchronisation of supply frequency and wheel speed will occur and if a three-phase supply is available the occurrence of the trouble may be obviated by distributing the lamps over the three phases of the supply and arranging them so that any one spot receives light from lamps connected in each phase.

In conclusion the authors wish to express their thanks to the British Thomson-Houston Company and the General Electric Company for providing much information concerning recent advances in the types of lamp under notice.

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